VEE
Martens

Ihr getreuer Freund
A. Martens.

ADDED BY THE TRANSLATOR.

Frontispiece.

HANDBOOK

OF

TESTING MATERIALS.

FOR THE CONSTRUCTOR.

PART I.

METHODS, MACHINES, AND AUXILIARY APPARATUS.

(IN TWO VOLUMES: VOL. I, TEXT; VOL. II, ILLUSTRATIONS.)

VOL. I. TEXT.

BY

PROFESSOR ADOLF MARTENS,

Director of the Royal Testing Laboratories at Berlin and at Charlottenburg.

AUTHORIZED TRANSLATION AND ADDITIONS

BY

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(STEVENS, '76,)

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TO

HIS DEAR FRIEND,

Professor Adolf Martens,

THIS BOOK IS DEDICATED

BY HIS DEVOTED ADMIRER,

GUS. C. HENNING.

PREFACE.

My book on Testing Materials for the Constructor is designed to be a counsellor to the constructor in all questions relating to the properties of his materials of construction. Therefore the book is divided into two volumes, each independent and complete in itself.

This first volume relates to the general properties of mate rials of construction, and especially to the art and science of testing materials as applied to machinery and superstructure.

To the description of the customary methods of testing I have added a presentation and discussion of the most important types of testing-machines and auxiliary apparatus, dwelling mainly upon the underlying principles of design, sources of errors, and on their calibration.

As this volume contains the manifold experiences of the laboratories under my direction, and as I have availed myself of the liberal arrangements granted by the publishers to fully illustrate, by figures and plates, the most important machines and instruments of all countries, I hope to produce a lasting benefit, not alone to my students, but also to manufacturers of apparatus, by my frank and candid criticism.

I do not wish to let this volume go forth without thanking those who, jointly with me and under my direction, have helped to increase our stock of knowledge to the best of their ability, and have hence directly assisted in this work.

How much the publishers have done to perfect this book, the book will show for itself.

A. Martens.

Berlin, April, 1898.

TRANSLATOR'S PREFACE.

IN spite of the existence of numerous able works on the same subject I do not hesitate to come before English-speaking engineers and manufacturers with a translation of Prof. Martens' book, because, being familiar with the others, I know that his treats the subject from a point of view so very different that to most, even the experts, the subject will appear like a new one.

Throughout the book, the author's views and explanations will be given with the utmost faithfulness, and the individual opinions or explanations of the translator will be clearly separated from the text of the original, either as additional paragraphs or as foot-notes.

The responsibility for criticisms, all of which are invariably of a friendly character, will thus be readily placed.

The German technical language is so wonderfully flexible that any idea or action can be readily expressed with absolute accuracy by a compound word which will be readily understood by all readers. Many of these words cannot be rendered by a single word in English. For instance, there is no English word which accurately and distinctively expresses a pressure-test of a long piece of material. The German calls this a "Knickprobe," which is scientifically accurate. Because there is no satisfactory English name, I shall call it a "thrust-test" in order to distinguish it from "crushing"-test. The term "compression-test" is correctly applicable only to a test in which the material is subjected to pressure on all sides, which

tends to "compress" it, i.e., to increase its density. It is positively incorrect when applied to a column test, in which the material is allowed to flow and bend in any manner possible without affecting its density. Other words, such as "rollability," "foundability," etc., etc., are used because they express technical properties and ideas correctly, which otherwise would require a complete sentence for clear definition. Moreover, they correspond to such words as "weldability," "fusibility," etc., etc., and follow well-established principles of etymology. Throughout the work Rankine's definitions of the meaning of the words "stress" and "strain" are adhered to.

The translator takes no credit for himself except as to the faithful reproduction of the thoughts, suggestions, and criticisms of the greatest authority in this field, and hopes that the publication of this work will help to introduce greater uniformity in testing and more accurate knowledge of materials, and may become a valuable guide to the constructing engineer.

GUS. C. HENNING.

NEW YORK, August, 1899.

CONTENTS.

(The numbers preceding each caption are those of the paragraphs. These numbers are used throughout the text and at the head of each page as well as under each figure.)

NOTATION.

SYMBOLS REGULARLY EMPLOYED THROUGHOUT THE WORK.

Numbers within parentheses in the text refer to paragraphs: those preceded by the letter L refer to the bibliographical index.

Sp. Gr.... s	specifisches Gewicht	= specific gravity.
W_v.... r	Raumgewicht	= volumetric weight.
W.... R	Litergewicht	= standard weight (Liter weight).
W_{sh}.... R_r	" , eingerüttelt	= stand. wt. shaken down.
W_f.... R_f	" , eingefüllt	= " " filled in.
W_s.... R_s	" , eingesiebt	= " " sifted in.
W_p.... R_e	" , eingelaufen	= " " poured in.
v, V.... i, I	Rauminhalt	= volume.
d.... $\mathfrak{d}$	Dichtigkeitsgrad	= density.
d_{-o}.... $\mathfrak{u}$	Undichtigkeitsgrad	= porosity.
L.... P	angreifende Kraft	= acting force, load applied.
a.... f	Querschnittsfläche des Probekörpers	= cross-sectional area of test-piece.
p	Beanspruchung	= load transmitted.
S.... σ	Spannung	= stress.
l_e.... l_e	Messlänge für die Feinmessung	= gauge-length for measurements of precision.
e.... λ	Verlängerung	= extension.
e_1.... ϵ	Dehnung der Längeneinheit	= strain; unit of elongation.
$e\%$.... δ	Dehnung in Procenten	= elongation %.
e_f.... α	Dehnungszahl	= factor of elongation.
$\left.\begin{matrix}E_t\\E_c\end{matrix}\right\}$.... E	Elasticitätsmodul	$= \left\{\begin{matrix}\text{modulus}\\\text{of}\\\text{elasticity}\end{matrix}\right\}\left\{\begin{matrix}\text{Tension.}\\\text{Crushing.}\end{matrix}\right.$
C_1.... ϕ	Querschnittsverminderung der Flächeneinheit	= reduction of unit area.

$C_{\%}\ldots q$	Querschnittsverminderung in Procenten	= % of reduction.
$S_P, e_P \ldots \sigma_P, \epsilon_P$, etc. u.s.w.	Proportionalitätsgrenze oder P-Grenze	= proportional limit, or P-limit.
$S_Y, e_Y \ldots \sigma_S, \epsilon_S$, etc. u.s.w.	Streckgrenze, Fliessgrenze oder S-Grenze	= yield-point, flow-limit or Y-limit.
$S_M, e_M \ldots \sigma_B, \epsilon_B$, etc. u.s.w.	Bruchgrenze, Höchstspannung od. B-Grenze	= maximum load tenacity, M-limit.
$S_R, e_R \ldots \sigma_Z, \epsilon_Z$, etc. u.s.w.	Zerreissgrenze, Zerreissspannung oder Z-Grenze	= load at rupture, ultimate stress, or F-limit.
$S_{El}, e_{El} \ldots \sigma_E, \epsilon_E$, etc. u.s.w.	Elasticitätsgrenze oder E-Grenze	= elastic limit, or E-limit.
$e' \ldots \epsilon'$	Dehnungsrest; bleibende Dehnung	= permanent set; ultimate extension.
$C \ldots \epsilon_q$	Querzusammenziehung	= contraction.
$C_f \ldots a_q$	Zusammenziehungszahl	= factor of contraction
m	⅓ bis ¼; Materialkonstante	= constant.
A	Formänderungsarbeit kgcm	= resiliency, inch-lbs.
$A_f \ldots a$	specifische Formänderungsarbeit $\frac{\text{kgcm}}{\text{ccm}}$ oder $\frac{\text{kgcm}}{\text{gr}}$	= specific resiliency, factor of resiliency.
$l_g \ldots l$	Messlänge, Probenlänge Probenhöhe	= gauge-length, test length or height.
$l \ldots l_g$	Gebrauchslänge	= finished length.
$l_d \ldots l_t$	Theilung	= divisions of length.
$E_q \ldots \xi$	Völligkeitsgrad	= equality ratio.
$n = l_g/\sqrt{a} \ldots n = l/\sqrt{f}$	Längenverhältniss	= length ratio.
$e\%_n \ldots \delta_n$	Dehnung für $l = n\sqrt{f}$	= elong. of $l_g = n\sqrt{a}$.
M	Moment der äusseren Kräfte in cmkg	= moment of external forces in inch-lbs.
$r \ldots \rho$	Krümmungshalbmesser	= radius of curvature.
$I \ldots \Theta$	Trägheitsmoment	= moment of inertia.
$\delta/l \ldots \delta/l$	Biegungspfeil	= ratio of deflection.
S_{PYM} or e_{PYM} — σ_{PSB} od. ϵ_{PSB}	Zugbeanspruchung ermittelt aus Zug- oder Druckversuchen	= Tension-stress determined from tension-tests.
$-S_{PYM}$ or $-e_{PYM}$ — $-\sigma_{PSB}$ od. $-\epsilon_{PSB}$	Druckbeanspruchung ermittelt aus Zug- oder Druckversuchen	= Crushing-stress determined from crushing-tests.
$S'_{P,Y,M}$ or $e'_{P,Y,M}$ — $\sigma_{P'S'B'}$ od. $\epsilon_{P'S'B'}$	Zugbeanspruchung abgeleitet aus dem Biegeversuch	= Tension-stress determined from transverse test.

$-S'_{PYM}$ or $-\epsilon'_{PYM}$	$\sigma_{P'S'B'}$ od. $\epsilon_{P'S'B'}$	Druckbeanspruchung abgeleitet aus dem Biegeversuch	= Crushing-stress determined from transverse test.
S' or ϵ' etc.	$\sigma_{,}$ od. $\epsilon_{,}$ u. s. w.	wenn diese Grössen sich auf den Biegeversuch beziehen	= Relating to transverse test.
S_t	....τ	Schubspannung	= torsional stress.
S_{t_e}	....γ	Schiebung	= distortion.
S_{t_f}	....β	Schubzahl	= factor of tortion.
Ss	....$\tau_{,}$	Scheerspannung	= shearing-stress.
$Ss_{M'}$, etc.	....$\tau_{B'}$, u.s.w.	Scheerfestigkeit	= " strength.
S_p	....$\tau_{,,}$	Lochspannung	= punching-stress.
$p_{M'}$ etc.	....$\tau_{B''}$, u.s.w.	Lochfestigkeit	= punching-strength
w and W	....g und G	Gewicht gr; kg	= lbs.
g	....g	981	= 32.2.
h	....h und H	Fallhöhe cm; m	= drop in ft.
i	....a	specifische Schlagarbeit	= specific work of impact.
H	....𝔋	Härtegrad	= hard: ess.
H_s	....𝔋r	Ritzhärte	= scoring-hardness.
T_n	....𝔍ₙ	Zähigkeitsgrad	= toughness.
F	....𝔅	Bildsamkeit	= plasticity.
B_f	....𝔅g	Biegegrösse	= bending-factor.
B_a	....w	Biegewinkel	= angle of curvature.
Fl	....𝔄g	Ausbreitung	= spreading.
Str	....𝔖tr.	Streckung	= stretching.
Exp	....𝔈g	Erweiterung	= expanding.
l_R	....ℜ	Reisslänge	= rupture-length.
	𝔚	Wöhlers Werthziffer	= Wöhler's quality-factor.
	𝔗	Tetmajers Werthziffer	= Tetmajer's quality-factor.

BIBLIOGRAPHICAL INDEX.

Bibliographical references in the text are placed in parenthesis, as follows: (*L 3*, 1896, vol. 7, p. 431). The number following the letter *L* refers to the bibliographical index; followed by the year, volume, and page of reference.

Under A will be found the reports of governmental testing laboratories regularly published in German, and the German, French, English, and American technical papers most generally read, and their abbreviated titles as used in the book. Under B, beginning with 100, are given the principal works of reference which are mentioned in the work.

A more complete bibliography has been omitted because the French official "Commission des méthodes d'essai des matériaux de construction" has been directed to prepare such a one as undertaken by R. Cordier, and to publish it. The "Repertorium der technischen Zeitschriften" publishes annually all references to papers appearing in technical journals.

A. Journals and Abbreviations.

a) Reports of Testing Laboratories.

1.	Mitthlg. Berlin.	Mittheilungen aus den kgl. technischen Versuchsanstalten; Berlin.
2.	Mitthlg. München.	Mittheilungen des mechanisch-techn. Laboratoriums der kgl. techn. Hochschule; München.
3.	Mitthlg Zürich.	Mittheilungen der Anstalt zur Prüfung von Baumaterialien am eidgen. Polytechnikum; Zürich.
4.	Mitthlg. Wien.	Mittheilungen des k. k. technologischen Gewerbemuseums; Wien.

b) Journals, German.

5.	Baumkd.	Baumaterialienkunde, internationale Rundschau.
6.	Bayr. Ind. Gew.-Bl.	Bayerisches Industrie- und Gewerbeblatt.
7.	Bg. hm. Ztg.	Berg- und hüttenmännische Zeitung.
8.	Centr. Bauv.	Centralblatt der Bauverwaltung.
9.	Civing.	Civilingenieur.
10.	D. Bauz.	Deutsche Bauzeitung.
11.	Dingl. J.	Dinglers polytechnisches Journal.
12.	Glas. An.	Glasers Annalen für Gewerbe- und Bauwesen.

13.	Mitthlg. Dampfk.	Mittheilungen aus der Praxis des Dampfkessel- und Dampfmaschinen-Betriebes.
14.	Org. F.	Organ für die Fortschritte des Eisenbahnwesens.
15.	Pogg. Ann.	Poggendorffs Annalen der Physik und Chemie.
16.	Rig Ind. Ztg.	Rigaische Industrie-Zeitung.
17.	Schw. Bauz.	Schweizerische Bauzeitung.
18.	Stahl.	Stahl und Eisen.
19.	Tech. Bl.	Technische Blätter.
20.	Thonind.	Thonindustrie-Zeitung.
21.	Verh. Gew.	Verhandlungen des Vereins zur Beförderung des Gewerbfleisses.
22.	Woch. Ing.	Wochenschrift des Vereins deutscher Ingenieure.
23.	Woch. Oest.	Wochenschrift des österreichischen Ingenieur- und Architekten-Vereins.
24.	Z. Arch.	Zeitschrift des Architekten- und Ingenieur-Vereins zu Hannover.
25.	Z. Bauw.	Zeitschrift für Bauwesen.
26.	Z. Berg. Hütt.	Zeitschrift für Berg-, Hütten- und Salinenwesen.
27.	Z. d. Ing.	Zeitschrift des Vereins deutscher Ingenieure.
28.	Z. Kälte Ind.	Zeitschrift für die gesammte Kälte-Industrie.
29.	Z. Oest.	Zeitschrift des österreichischen Ingenieur- u. Architekten-Vereins.

c) Journals, French and Belgian.

30.	An. Belg.	Annales des Traveaux publics de Belgique.
31.	An. Ind.	Annales Industrielles.
32.	An. M.	Annales des Mines.
33.	An. P. C.	Annales des Ponts et Chaussées.
34.	Gén. Civ.	Génie Civil.
35.	I. Civ.	Comptes rendus de la Société des Ingénieurs civils.
36.	Ind. Min.	Bulletin de la Société de l'Industrie minerale.
37.	R. Chf.	Revue générale des Chemins de fer.
38.	R. Ind.	Revue industrielle.
39.	R. M. Met.	Revue universelle des Mines et de la Métallurgie.
40.	Soc. Enc.	Bulletin de la Société d'encouragement.
41.	Soc. Mulh.	Bulletin de la Société industrielle de Mulhouse.

d) Journals, English and American.

42.	Am. Eng.	Transactions of the American Society of Civil Engineers.
43.	Am. Jour.	American Journal of Science and Arts.

44. Am. Mec.	Transactions of American Society of Mechanical Engineers.
45. Am. Min.	Transactions of the American Institute of Mining Engineers.
46. Civ. Eng.	Proceedings of the Institution of Civil Engineers of London.
47. Eng.	The Engineer.
48. Engng.	Engineering.
49. Eng. Min.	Engineering and Mining Journal.
50. Eng. News.	Engineering News.
51. Fr. Inst.	Journal of the Franklin Institute.
52. Iron.	Iron.
53. Iron A.	The Iron age.
54. Ir. and St.	Journal of the Iron and Steel Institute.
55. Proc. Mech. Eng.	Proceedings of the Institution of Mechanical Engineers (London).

e) Additional.

56. Z. f. Instrkd.	Zeitschrift für Instrumentenkunde.

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C. Index of Names.

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INTRODUCTION.

1. The practical knowledge of properties of materials is an important part of technology. It is the study of the properties and of the useful value of materials used in technology.

Technology, however, is also concerned in their production and distribution. This definition elucidates the importance of this territory of technological activity. Without the steady perfectioning of our knowledge of the properties of materials used in the construction of machines, or with which we operate them, constant advance and progress of industries would not be possible. Everywhere in manufactures will the inquiry as to properties of materials used or to be obtained turn up in the foreground. The question as to the value of the materials is frequently decisive in the inauguration of enterprises. The greater or lesser difficulty in obtaining materials has frequently been the cause for the establishment or decadence of entire industries. Industries, e.g., founded upon the occurrence of petroleum, natural gas, etc., etc., in a given district, lose their profitableness with the drying up of the sources of their supplies, when they cannot bear the increased cost of transportation from other places, or when the method of operation does not permit their use of materials having different qualities.

How important a correct knowlege of materials is considered in manufacture is readily recognized when it is

seen how, e.g., all our metallurgical and other establishments which produce, and fabricate finished from raw materials, are equipped with laboratories for the investigation and analysis of the raw materials and of the product. A plant like that of Krupp, in Essen, has numerous chemical laboratories, as well as such for determining strength and other mechanical and physical properties of metals and other materials of construction. Even smaller works have testing-machines and employ engineers, with frequently numerous assistants, for the constant testing of their materials. In shops using the artificial products extensively organized testing laboratories are also frequently found.

I refer to the bridge-shops, which frequently possess powerful testing-machines,* to the production of wire and of rope, in which dozens of machines for testing the properties of the wires and ropes produced are to be found in addition to complete laboratories for investigating the electrical behavior of the telegraph cables manufactured. Our railways and military, etc., etc., have special departments of administration which are solely occupied with purchase, tests, preservation and distribution of materials used by them.

Wherever there is a question of the use of large quantities of materials a contract is made between the seller and buyer, in which the properties required in the material are specified with utmost precision. Special officers of railways, for instance, are detailed to supervise the delivery of rails; engineers have their inspectors for bridge structures; military authorities for armor, guns, projectiles, etc., to supervise the entire manufacture, and to keep watch that the materials be manufactured with the utmost care, and that the specifications and requirements are met in every minutest detail.

* In the United States there are the Union Bridge Company's machine at Athens, Pa., of 600 tons capacity (*L 53*, 1891, p. 142), and the Phœnix Iron Company's machine at Phœnixville, Pa., of 1200 tons capacity (*L 48*, 1887, p. 413) for testing bridge members. The Keystone Bridge Works, Pittsburg, Pa., has a 500-ton machine.—G. C. Hg.

The young engineer must, therefore, acquaint himself with the properties of materials, as the time when he may be called upon to assume charge of inspection and pass upon the value or the defectiveness of material may come to him at an early age.

The responsibility which he must thereby, as a rule, assume may be a very grave one, for upon his decisions depends the welfare of the producer as well as of the purchaser; even the public interest may be injured by neglect of his duties, because the safety of a structure may be endangered by defective material. Should he be the representative of a manufacturer, or the deputy of an administrative department, or even a middleman, acting as expert between both parties, his knowledge and experience will invariably be heavily taxed.

Even in later years the engineer cannot remove the direct responsibility for the good properties of the materials used in construction or processes, in whichever branch of industry he may be occupied. It is he who, as manufacturer, manager, or responsible officer, writes specifications and signs contracts. He cannot do this profitably without an exact knowledge of and manifold experience in the department of testing materials. His responsibility will not be less direct in these positions than when acting as inspector of materials. For upon the skilful and practical wording of specifications frequently depends the productivity and endurance of his machines and constructions, quite as much as upon the perfection of the design.

He can play a progressive or an injurious part in an industry according to the specifications which he writes.

This work shall give a systematic representation of the most important points to be observed in testing materials. Practical knowledge of machines, instruments, and methods especially shall be disseminated, to which are to be coupled the properties and utility of materials, particularly as applied to machine design. Moreover, it is not to be merely a guidepost to the beginner, but the author hopes to be able to offer

to the experienced engineer, also, much relief and some benefit in the execution of difficult tasks.

2. Two classes of materials may be recognized. In the first group may be classified such materials which form the framework, foundation, members of machines or constructions. It is the intention to maintain these in their original shapes permanently (columns, trusses, machine frames, etc.), or to change them in a gradual or definite manner, if not to let them return to their original form after use (springs, etc., etc.).

Henceforth I desire to call these

M a t e r i a l s o f c o n s t r u c t i o n , o r b u i l d i n g m a t e r i a l s .

To these belong metals, wood, stone, etc., etc.

The second group, for purposes of distinction, I shall designate as

M a t e r i a l s o f c o n s u m p t i o n ,

because they are consumed or transformed in the processes or industries in which they are used, as a rule doing work requiring replacement in order that the process may be continuous. To this group belong water, coal, lubricants, etc., etc.

This separation in two groups is not a rigid one, for even the materials of construction are in a certain sense "consumed," and a material intended generally for consumption may occasionally become part of a structure.

I. Technological Properties of Materials of Construction in General.

A. Mechanical Properties.

3. The bed, pedestal, frame of a machine may change its shape under stress—e.g. in a steam-engine by the piston pressure; in a press by the plunger; in the lathe while taking a cut—only to such a small degree that noticeable relative displacements of individual parts do not occur. It must be ascertained of the material of which the separate parts consist that it answers these requirements, that it behaves as nearly as possible like a rigid body and can safely bear the various loads to which it is subjected in the steam-engine, the press, the lathe. The movable parts of machines must, however, answer their purpose in a similar manner, being intended to transmit motion and loads from one part of a machine to another, while they are constrained to travel in prescribed paths, by the shape of the rigid parts. The piston, the plunger, the connecting-rod, the crank of the steam-engine are examples of this case. But these parts as well, considering each for itself, must not change their shape to a noticeable degree; they should be constructed of materials as rigid as possible.

Physics teaches us that there are no strictly rigid bodies, that in so-called rigid bodies all particles are in motion, and that a body is called "rigid" when it does not change its shape, of itself, under the influence of gravity, but which opposes a resistance to every attempt to change its external

shape. Accordingly absolute rigidity must not be expected of materials used for the constructional parts above mentioned, but a definite resistance for the purposes intended under a determined change of shape must be satisfactory. In other words, a definite degree of rigidity must be demanded of them.

The material of construction must be resistant.

4. Other parts of machines must do a certain work, undergoing material changes of shape under the effect of external forces, and again returning to their original shapes when released. Such details are found in the suspension springs of locomotives; buffer springs, resisting the shock between cars; the bow which launches the arrow; etc., etc. Materials possessing these properties are called "elastic."

The property of elasticity is requisite in all materials of construction in addition to resistance.

5. Bodies which slide upon each other like steam-engine crossheads, pistons in cylinders, shafting journals in boxes, produce friction and abrasion, which are both accompanied by considerable absorption of work, and as work costs money, must be avoided by the careful constructor and must be reduced to a minimum. Experience teaches that hard materials are abraded less than soft ones. The hard body resists penetration by a foreign body more than a soft one. Hardness and softness cannot, however, be considered as opposites, but the latter must be considered merely as a lesser degree of the former.

Materials of construction should therefore possess the property of hardness as well.

6. It happens in our machines occasionally that the forces acting on some parts are applied suddenly, even by impact, and experience teaches us that some bodies do not withstand such loads. They break like glass, while others withstand

even heavy impact, sometimes undergoing considerable change of shape and retaining it. Materials of the first variety are called brittle, while those of the second are commonly called tough (ductile).

Toughness and brittleness are therefore properties of materials which must be subject to examination.

7. Thus far properties of materials were considered which were required of them for constructive purposes, and we must now consider those which they must develop in order that they may be readily given the forms required for the desired detail. To keep these two groups of properties easily separated and readily identified hereafter, arbitrary names shall be adopted for them, never forgetting, however, that such divisions into groups are by no means precise or definite.

The properties first treated of we shall call the mechanical properties of materials, because these are predominantly required in the mechanical application of loads in construction.

The properties now to be considered we shall call technological properties, because they are in predominant evidence in the fabrication of materials into constructive detail.

B. Technological Properties.

8. The transformation of materials into constructional detail is carried on in many ways. The materials must therefore develop manifold properties; they must be "workable," i.e. they must be in such condition or capable of being put in a condition that they can be transformed into the desired final shape. This can be attained by

1. Division, i.e. separation into individual parts of the mass;

2. Transformation of the mass without separation; and

3. Agglomeration, i.e. uniting of various parts into one mass.

9. Among the processes of the first kind, viz. division, are working by edge-tools, such as wedges, shears, saws, chisels, gouges, drills, etc., etc. To make these tools serviceable the material must possess the properties previously described, to a more or less pronounced degree. Here the properties of resistance, elasticity, hardness, toughness, and brittleness come into question.

10. In the second group, in which fabrication is carried on by transformation, the preceding properties must be considered as well, but in addition there are other properties not previously discussed.

Some materials, especially metals, may be transformed into different shapes in their cold state by hammering; these are said to be malleable. Other substances yield to external forces more or less, and their shape is permanently changed; they are called formable, kneadable, pressable, mintable, drawable, etc. These properties of malleability and plasticity are not strictly separable, and differ mainly in degree.

The nomenclature of these properties in particular is derived from the methods of fabrication to which the material was subjected.

11. Other substances which are but slightly malleable or formable in their ordinary condition may, by certain processes, be transformed into bodies readily malleable and formable. When this becomes possible by the application of heat, and they are wrought by hammers, rolls, etc., the material is said to be forgeable, rollable, etc.

12. Sometimes it becomes possible to soften a body without application of heat, by adding another material which permits of its being moulded, and after this transformation removing the added material, as is done in moulding clay and porcelain, by addition of water. In this condition the material is called plastic.

Formability and plasticity are synonymous.

13. Some materials can be melted by heat; they are fusible. When the melted mass can be cast in moulds, and thus given new shapes, the material is said to be foundable.

14. In the third group, in which transformation proceeds by agglomeration, special properties of materials are called into play which enable two separate pieces of the same or of a different kind to be united to form a single body. These are the properties: weldability, solderability, puttyability.*

15. Weldability permits the direct junction of two surfaces of material which have been made soft and plastic by great augmentation of temperatures and then brought into closest contact by hammering or pressing, and thereby united rigidly.

16. Soldering, gluing, puttying are done by the interposition of a special substance, such as glue, solder, putty, between the surfaces of bodies, which possesses a property causing it to adhere rigidly to each surface, and which upon desiccation possesses enough resistance in itself to insure the coherence of both bodies. Bonding stones by means of mortar may be placed in this group.

C. Physical Properties.

17. In addition to the technological properties above considered which must be possessed by materials suitable for structural detail or which it must develop during conversion into such, there is a series of properties inherent in materials in every shape, and which, in addition to the first mentioned, go to make up their physical and chemical character. These

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* I do not hesitate to use these words, because they express the intended ideas accurately, and are etymologically correct, however odd they may appear to some critics.—G. C. Hg.

form two additional groups, the physical and chemical properties, to be distinguished.

While these properties of course do not concern the constructor as directly as the above-considered technological properties, yet he must at times know their degree most accurately if he desires to calculate and construct reliably and correctly.

18. In the first place, as a physical property of materials, specific gravity and density must be considered. Hereafter the term *specific gravity* shall be used to designate the true specific gravity of the material itself, which must be determined from pieces free from interstices.

The idea "density" shall be interpreted in consonance with the practical objects of this work and common usage of industrial life. The terms, "the casting is porous," "the steel is unsound," "the ingot is honeycombed," etc., etc., are frequently met with. These are to indicate that the casting contains voids, the steel is fissured, the ingot is piped in center because of shrinkage, having irregular cavities, with rough, jagged walls, produced by "shrinkage," i.e., the contraction of the mass during cooling. These and many other terms are but abbreviated expressions to indicate that the apparent external volume is not all occupied by material without voids. In the following a body filling the space occupied by it without voids shall be called "dense."

19. From this it follows that the specific gravity of a dense body is equal to the specific gravity of the material composing it. A body not dense (porous) in this sense has, therefore, a lesser specific gravity than that composing it.

20. The letters Sp.Gr. shall hereafter denote specific gravity of the material, while "W_v" shall stand for the weight of the unit of volume of the material, the volumetric weight.

When reference is had to a liquid or to a heap of fine material (grains, powder) which does not occupy a definite volume of itself, but which can only be measured by cubic measures or by weighing its mass, the volumetric weight refers to cubic inch or cubic foot (liter or cubic meter), and these shall be considered the standards. In Europe this is called L i t e r w e i g h t.

In the case of loose materials, the method of filling the cubical measure must also be considered. The weight of a cubic foot of a powder, e.g. cement, lime, etc., varies accordingly as the powder is filled in in small quantities, run in as a whole, is sifted in, or shaken down. The use of the number W must therefore, at the same time, refer to these conditions when it is to have a definite meaning and also be universally understood. I therefore introduced the following standard notation in the Charlottenburg Testing Laboratory: *

$W - R$ = Litergewicht—Standard Weight (Literweight).
$W_{sh} - R_r$ = Litergewicht eingeruettelt—Standard Weight shaken down.
$W_f - R_f$ = Litergewicht eingefuellt—Standard Weight filled (in lots).
$W_s - R_s$ = Litergewicht eingesiebt—Standard Weight sifted in.
$W_p - R_e$ = Litergewicht eingelaufen—Standard Weight poured in.
W_{sh} = Shaken down until no further diminution of volume occurs.
W_f = Filled by spoon, etc.
W_s = Carefully sifted under definitely stated conditions.
W_p = Poured in until full, under precise conditions.

21. The r e l a t i o n between the v o l u m e t r i c w e i g h t and s p e c i f i c g r a v i t y—according to our definition in the case of perfectly solid material, its d e g r e e of d e n s i t y—is expressed by $d = \frac{W_v}{\text{Sp.Gr.}} = 1$; in the case of defective, porous, fissured, piped, etc., material, $d < 1$.

It is common practice to give the p o r o s i t y instead of the degree of density; this is represented by

* This notation does not quite answer in the English language, and I have therefore modified it to suit conditions. However, as this German notation has become practically universal in engineering publications in Germany, Austria, Russia, Switzerland, Denmark, and Sweden, I give it in full, with the German names. No misunderstanding can thus arise. —G. C. Hg.

$\text{Sp.Gr.} - \frac{W_v}{\text{Sp.Gr.}}$, and is not so readily calculated, and is moreover given by d. Where, hereafter, the *degree of porosity* or degree of *lack of density* is exceptionally to be given, it will be expressed by $1 - d$.

22. A body of degree of density $= 1$ in the sense as here used, or which fills the volume occupied voidless, need by no means be homogeneous throughout; it may be a voidless conglomeration of particles which are in themselves similar or dissimilar, forming units in a certain manner, joined directly or by the intermediary of bonding members, without voids. This internal structural arrangement of bodies of individual, similar or dissimilar particles (as a rule of different Sp.Gr.) is very frequently met with in our materials; it is to a large degree responsible for their character and value. It is the *internal structure*, which also determines essentially the character of surfaces of rupture, the structure of fractures.

23. According to the internal arrangement, the *structure*, materials can be distinguished as those with or without structure, *structural* or *structureless*.

Among the first are classed gaseous, liquid, and some solid bodies, such as glass, pitch, etc. Glass is characteristic of structureless materials, so that they are commonly called *vitreous*.

Most materials show a definite structure when in the condition in which they are used in industries, which is commonly specially designated by technical terms, according to the special appearance of ruptured or separated surfaces, as granular, fibrous, fibriform, lamellar, crystalline, reticular, cellular, etc., etc. Latterly distinctions are made as to *visual* and *micro-structure*, the first relating to structure plainly observable by the naked eye, while the latter is that which can be identified only by the microscope.

Those materials are *fibrous* which are composed of fibres, such as some minerals (asbestos), wood, etc.

[This term is also applied in England and the United States to rolled iron, although its use in this connection is quite incorrect and inappropriate: iron is not composed of, nor does it break up into, fibres; it should be called "fibriform," and this term will hereafter be used.—G. C. Hg.]

Fibriform (sinewy) correctly describes wrought iron which has been rolled in one direction; its fracture presents an appearance like that of fibres; mica is lamellar; also thin sheets of rolled wrought iron, etc. All the structure forms have the parallel arrangement of the particles in common; in the case of the fibrous and fibriform bodies the particles are filiform, while in those which are lamellar they are as superposed plates. According to the degree they are called coarsely or finely, long or short fibrous, fibriform, or lamellar.

A crystalline, reticular, cellular structure is found in many kinds of stone and in some metals used in construction. When the crystalline structure is more or less regularly developed so that certain surfaces or directions are predominant in fracture surfaces, additional special terms are used to designate them, e.g., specular (block tin), filiform, needle-shaped, columnar, lamellar-crystalline, etc., etc.

When the surfaces are irregular, more or less uneven, and appear irregularly arranged, the structure is defined as granular, and distinction is made between fine- and coarse-grained. Very finely granular or very finely fibriform structure frequently assumes a perfectly smooth glossy appearance like satin, and is then characterized accordingly.

Cellular arrangement is particularly found in metals and alloys, such as iron and steel, when different components, or sub-alloys, separate from the rest of the mass, or in a certain manner form envelopes about individual particles, such as graphite in pig iron.

24. Fibrous, fiibriform, lamellar, and even crystalline materials frequently develop the property by which they become

more readily separable in certain directions than in others; they possess the property of ("cleavage") splitting, to a more or less pronounced degree, as wood, stone, etc.

25. A property of solid materials, which is of exceedingly great importance to the technologist and for the further elucidations in this work, and which is also possessed by liquids, is that by which they change their volume by only an infinitely small amount when subjected to external universal pressure, provided they have a degree of density = 1, i.e., when they are free from internal voids; under these conditions they do not undergo a change of shape, so long as their internal structure does not provide resistances different in different directions. This important property makes possible, e.g., the phenomenon that even very elastic bodies such as rubber behave as though inelastic when they are surrounded by rigid surfaces, or are acted upon on all sides by forces tending to change their shape.

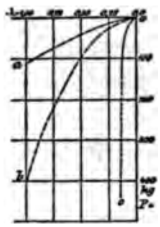
When water comes in contact with highly compressed air in a compressor, it absorbs the air, and the compressor thus loses its effectiveness, after all the air has been absorbed and entirely replaced by water. It is customary to minimize this action by pouring a layer of oil on the water under certain conditions; but this succeeds only when violent agitation of the water is prevented. But if it were attempted to use rubber as a substitute for the elasticity of the air, the success would be equal to zero. The rubber, under the effect of universal pressure, would suffer only insignificant change of volume and an inelastic shock, equal to that when the compressor is filled with water, would occur. For this reason it is more advantageous to use rubber bags filled with air; these can be used under very heavy pressures, and in long-continued service, without deterioration of the rubber. Rubber buffers must, for the same reasons, be held in chambers with ample clearance; otherwise they will lose their effectiveness totally. In short, the fact is established

that the elastic properties of bodies can only be utilized when they are subjected to forces in such manner that there is freedom of change of shape in at least one direction. In order to illustrate this proposition and to introduce students to the science of testing materials, I have the custom of making the following rough test on the 100 t. Pohlmeyer machine during their first hour of practical work.

Table 1. Pressure Test of Rubber Cube.

The machine was rapped before each reading.

Load Reading. Pa kg	Difference. ΔPa kg	Force. $P = \Sigma Pa$ kg	Reading of Scale. A cm	Difference. ΔA cm	Shortening. $-\lambda = \Sigma A$ cm	Remarks.
		(*a*) Body loaded unconstrained.				
0	—	0	0.25	—	0.00	Metric dimensions are given because comparisons of numbers is the object of the table.
20	20	20	0.50	0.25	0.25	
45	25	45	0.75	0.25	0.50	
80	35	80	1.00	0.25	0.75	
120	40	120	1.25	0.25	1.00	
100	− 20	100	1.00	− 0.25	0.75	
70	− 30	70	0.75	− 0.25	0.50	
40	− 30	40	0.50	− 0.25	0.25	
20	− 20	20	0.25	− 0.25	0.00	
		(*b*) Body enclosed on two sides.			Fig. 1.	
25	—	0	2.50	—	0.00	
55	30	30	5.75	0.25	0.25	
125	70	100	3 00	0.25	0.50	
260	135	235	3.25	0.25	0.75	
420	160	395	3.50	0.25	1.00	
155	− 265	130	3.25	− 0.25	0.75	
88	− 75	55	3.00	− 0.25	0.50	
50	− 30	25	2.75	− 0.25	0.25	[1] The body already had a clearance of 0.15.
20	− 30	− 5	(2.50)[1]	(− 0.25)	—	
		(*c*) Body enclosed on all sides.			Fig. 1.	
20	—	0	2.50	—	0.00	[2] Mainly to fill voids existing in apparatus.
450	430	430	2.65	0.15	0.15[2]	



A rubber cube of about 2.36 in. (6 cm.) length of side is loaded at first between two plane pressure-plates, then placed in a cast-iron frame with two sides bearing against it, as at *a*, Fig. 1, and finally further constrained by two cheek-pieces *bb*, so that it is enclosed on all four sides. The forces and def-

ormations produced are measured and recorded as in Table 1. During the test the predetermined depressions of piston are read off on the attached scale and the loads at these instants are noted. The weighing-machine is intentionally caused to work with considerable friction during this first test, and hence does not indicate any load, even for very considerable deformations, in order that students at once learn to pay attention to errors which may exist in the testing-machines and apparatus, and must guard themselves against errors of observation. Then the actual test is undertaken, while the machine is rapped by a wooden mallet of such capacity that the impact and vibration almost entirely overcome the frictional resistances, and it is shown to be possible to obtain useful results even with an apparatus relatively crude.

26. Aside from the effects just described of the impossibility of material change of density in a body of density = 1, this property comes into play in working materials by hammering, forging, rolling, drawing, minting, etc. In all of these processes lateral pressure is exerted on the body to be transformed and it is allowed to flow in one or two directions; it assumes new shapes without material change of density. This property of materials will again be discussed further on when considering the detail of methods of test, to explain a number of phenomena occurring thereunder.

In order to furnish an example, lead bodies are cast, during the hours for laboratory work, in heated moulds open at the top, which are allowed to cool slowly and solidify as dense as possible; these are then subjected to the compression test, once unconstrained and again completely enclosed in dies as in the minting-press. The specific gravities are determined before and after test. The following results have thus been obtained, which are supplemented by those obtained by Kick and Barba (*L 100*, p. 81; *L 101* u. *102*, Vol. III).

The apparatus for universal compression is arranged as shown in Fig. 2; it has also been used for tests for brittle

substances under universal pressure. The apparatus is reinforced by a jacket pressed on as in gun construction.

Table 2. **Pressure-tests of Lead Bodies.**

Before and after each test, specific gravities Sp. Gr.$_1$ and Sp. Gr.$_2$ were determined. The bodies were tested when unconstrained between plane surfaces and when completely enclosed (Fig. 2).

Shape of Test-piece.				Final		Specific Gravity.					
Section.	Length l in.	Section a sq. in.	Volume V cub. in.	Stress in Pounds per sq. in.	Crushing of Unit Length $-e_1$	Before Test. Sp. Gr.$_1$	After Test. Sp. Gr.$_2$	Diff.	Weight W oz.	Volumetric Weight W_v	Degree of Density $\frac{W_v}{\text{Sp. Gr.}_2}$
	a. Bodies crushed without restraint.										
1. Circle.	1.18	1.096	1.293	60 440	0.84	1.1045	1.1047	0.0002	.5178	1.1073	1.002
2. Square	2.36	5.534	130.660	16 080	0.69	. . . . . .	. . . . .	. . . . . .	. . . . . .	. . . . . .	. . . . . .
3. Circle.	1.18	1.096	1.293	43 660	0.83	1.1354	1.1364	0.0010	.5262	1.1257	0.991
4. "	1.18	1.088	1.287	48 680	0.85	1.1347	1.1360	0.0013	.5263	1.1313	0.997
5. "	1.18	1.096	1.293	21 330	0.65	1.1053	1.1057	0.0004	.5158	1.1028	0.998
6. "	1.18	1.096	1.293	28 440	0.64	1.1050	1.1053	0.0003	.5159	1.1031	0.998
	b. Bodies universally constrained										
1. Circle	1.18	1.096	1.293	60 440	0.06	1.1048	1.1040	− 0.0008	.5169	1.1059	1.001
3 and 4. Circle.	1.18	1.096	1.293	26 880	—	1.1343	1.1358	0.0015	.5276	1.1287	0.994
5 and 6. "	1.18	1.096	1.293	28 440	0.03	1.1052	1.1059	0.0007	.5158	1.1031	0.998

27. Bodies containing pores (voids) behave differently from those having a density = 1. These can be compressed by universal, and also sometimes by uni-directional pressure, the compression being perhaps temporary when the material is of itself of an elastic nature, or permanent when but slightly elastic, or so resistant that the pressure of the occluded gaseous materials cannot rehabilitate the original shape, or when they might have escaped during test. Such porous elastic bodies can then be used as springs or buffers when they are completely encased. The material of which they are composed is in that case, however, not materially the cause of the developed elasticity. The essential part is the gaseous component.

The effect of the occluded air or gases on the material containing them is not exhausted by the phenomena of change of density under pressure. I merely desire to indicate that substances like modelling clay, gutta-percha,

kneaded bread, glaziers' putty, etc., which are very plastic under pressure slowly applied, may appear quite elastic under the effect of impact, and may resist an attempted rapid change of shape (*L 100*). Bread-dough may be given any shape by kneading, but the shape produced can hardly be changed by dropping it onto a hard base. These substances contain air, which fact can be readily verified by an air-pump acting on the material immersed in oil.

In order to demonstrate the degree of compressibility, different kinds of wood are tested in the apparatus shown in Fig. 2, the cellular structure of which is shown by microscopic sections, during the laboratory work of students. These tests are instructive and show that nearly the same volumetric weight may be obtained in wood, which is nearly the specific gravity of cellulose; i.e., the body of density $d < 1$ may be compressed nearly to a density of $d = 1$. The porosity of wood can be determined by the compression test; it appears that this is quite definite for each variety of wood, if we may judge from the tests made. These results are given in Table 3.

28. Among the physical properties may be counted the resistance offered by bodies to penetration or indentation by a foreign body, its hardness. Attention has been previously called to this (*5*), and as its determination is more fully discussed later on (*341*, etc.) its enumeration must here suffice.

29. Besides the physical properties thus described in detail, the behavior of substances during heating and cooling must be considered, i.e., the capability of change of volume during thermic changes, the conductivity, radiation, absorption of heat, or specific heat, the melting-point, boiling-point, evaporation-point, the point of congelation, etc., etc. Every good schoolbook on Physics treats of these properties, and it would lead us too far to take up these matters here (*L 103* and *104*). The same is true of electric and magnetic properties, electric and magnetic resistances, conductivity, capacity, etc., etc.

Table 3. Compression-tests of Wood.

The bodies were treated under universal constraint as in Fig. 2; $d = 1.18''$ (= 3.0 cm); $l = 1.18''$ (= 3.0 cm); diameter of hole $d_1 = 1.189''$ (= 3.015 cm); diam. punch = 1.187″ (= 3.02 cm); area of hole $\delta_1 = 1.11$ sq. in. (= 7.16 sq. cm). All bodies were subjected to a max. load = 59,700 lbs. per square inch (= 4200 kg cm).

Kind of Wood.	Crushing Limit $-S_Y$ pounds per sq. in.	After Test. Length l_1 inches.	After Test. Volume v in cub. in.	Weight in lbs.	Volumetric Weights before Test. W_v	Volumetric Weights after Test. W_{v_1}	Degrees of Density $d=\frac{W_v}{W_{v_1}}$
a. Pine: 1	7878	0.4370	0.4849	0.0237	0.509	1.36	0.37
2	7935	0.3976	0.4404	0.0228	491	44	34
3	8688	0.4646	0.5148	0.0251	537	35	40
4	(10880)*	0.4646	0.5154	0.0252	542	36	40
5	7622	0.3779	0.4190	0.0221	485	46	33
6	7906	0.4016	0.4453	0.0223	479	38	35
Mean	**8091**	—	—	—	**0.507**	**1.392**	**0.365**
b. Oak: 1	6300	0.4291	0.4758	0.0257	0.554	1.50	0.37
2	6243	0.4606	0.5118	0.0254	547	38	40
3	7864	0.5471	0.6070	0.0316	667	44	46
4	7892	0.5590	0.6190	0.0715	672	41	48
5	8546	0.5630	0.6221	0.0317	680	41	48
6	9044	0.5431	0.6088	0.0330	710	51	47
Mean	**7651**	—	—	—	**0.638**	**1.442**	**0.404**
c. Red beech: 1	7693	0.5197	0.5752	0.0299	0.637	1.44	0.44
2	7338	0.4764	0.5288	0.0297	639	56	41
3	7992	0.5158	0.5716	0.0302	649	46	44
4	8688	0.5118	0.5691	0.0294	632	43	44
5	8006	0.5197	0.5752	0.0300	645	44	45
6	7920	0.5000	0.5550	0.0303	652	51	43
Mean	**7935**	—	—	—	**0.642**	**1.473**	**0.433**
d. Mahogany: 1	11230	0.5433	0.6014	0.0319	0.686	1.47	0.47
2	13080	0.5551	0.6160	0.0315	688	42	47
3	10760	0.5943	0.6588	0.0325	703	36	52
4	10280	0.5275	0.5856	0.0328	705	53	46
5	9386	0.5709	0.6344	0.0315	677	37	49
6	9954	0.5866	0.6514	0.0322	688	37	50
Mean.	**10780**	—	—	—	**0.691**	**1.423**	**0.485**
e. Ash: 1	9000	0.5787		0.0328	0.704	1.42	0.50
2	8035	0.5236	0.5795	0.0321	703	57	45
3	9650	0.5748	0.6344	0.0348	743	52	49
4	10210	0.5866	0.6527	0.0356	762	51	50
5	10520	0.5945	0.6588	0.0348	745	46	51
6	11290	0.6102	0.6771	0.0350	752	43	53
Mean...	**10020**	—	—	—	**0.735**	**1.501**	**0.497**

* Loaded too rapidly; hence resistance excessive.

Books on Physics and Electrotechnics should be consulted for a knowledge of these.

D. Chemical Properties.

30. Chemical properties of materials of construction are those which are determined mainly by the chemical composition and which are changed as soon as the chemical condition changes. We are therefore not really concerned with properties the study of which lies exclusively in the domain of the chemist, but predominantly with those which concern the constructor as deeply as the chemist. Further on this special field will be treated by itself, i.e., the dependence of the technological properties of materials in particular, e.g. of metals, upon their chemical composition. But as we cannot examine into this and other fields before we have taken a general survey of the requirements which are demanded of the possibilities of a material, especially before the knowledge of the determination of the properties in particular has been developed, we shall merely touch upon this subject here, and will treat it more fully in the proper place.

All of the enumerated properties are materially influenced by the chemical composition; but it must be here pointed out that the chemical composition primarily determines the behavior of materials under chemical influences; e.g., their resistance to acids, alkalies, moisture, air, steam, etc.

The external appearance as well, color, sheen, degree of polish, permanence of polish, etc., and other properties are ultimately dependent upon chemical composition.

II. Testing Materials.

31. As the previous division is devoted to an enumeration of the properties of materials which concern the constructor, it now becomes necessary to establish a representation or a measure of degree of perfection of these properties possessed by the different materials. This problem is the most important subject of this volume.

Properties of materials can be modified or affected by manifold circumstances. Slight changes in chemical composition of an alloy frequently have an important influence on the behavior of the structural part made therefrom, and may increase or decrease its value materially. The method of production of materials influences their mechanical behavior in structures. In addition there is the effect of mechanical manipulation during fabrication, which becomes important in iron. Rapid cooling, heating, hammering, cold-rolling, etc., materially affect the properties of most metals. It is of the greatest importance to follow by measurements the degree of quality changes, to furnish the constructor with constants for his calculations, and to establish the knowledge of value of materials. This is done by measuring and comparing the most important properties of materials, and that part of the knowledge of materials which relates principally to this subject is called the study of T e s t i n g M a t e r i a l s.

The discussion of Testing Materials can be appropriately divided into several groups, and the divisions adopted in the

consideration of the properties may be most conveniently retained. But for reasons previously stated other properties can here be touched upon but superficially, and it will be advisable to consider the measurement and comparison of mechanical and technological properties not as strictly separated from each other. This is not really necessary, as it has been previously shown that the line of demarcation between the two groups cannot be definitely drawn.

A. Resistance of Materials.

32. The characteristic property of solid bodies, as has been shown, is their resistance to change of shape. The deformation is produced by external forces acting upon the body, loading it. The methods of loading by external forces, and the number of kinds of stress * to which it may be subjected simultaneously, may be manifold. The forces may tend to rupture, to crush, to bend, to twist, to shear, to buckle, etc.; and just as many kinds of resistance against deformation are called into play, which are designated "stress" and named accordingly. We therefore recognize tensile, crushing, flexional, torsional, shearing, thrusting resistance, or stress.

In the study of strength of materials all these various kinds of resistances to deformation, and the theoretical enunciation of laws of deformation, are derived from a few fundamental properties of materials. These fundamentals considered as established, it will suffice to determine and consider here only those ideas which are of importance for a knowledge of methods of testing.

In doing this we must call attention to a difference of

* The term "stress" throughout this work shall be used in the sense of Rankine's definition, as that force transmitted to each unit of section of the material loaded. Hence "stress" will always mean "load per sq. in."—G. C. Hg.

method of treatment employed by us and that used by mathematicians in the development of the science of resistance of materials. The mathematical study of resistance of materials treats mainly the elastic deformations of bodies, while here particular attention must be devoted to the occurrences technologically important during permanent deformation.

A. Tensile and Crushing Resistance.

1. Definitions.

Tensile Resistance.

33. Considering two equal forces P, Fig. 3, to act on a very long prismatic body in the direction of its longitudinal axis, we may assume that the forces are equally distributed over the sections aa and bb whose area is equal to a. The force sustained or transmitted by the unit of area, the specific force or the load, will in future be designated by p; hence $p = P/a$.

This load is resisted by forces generated within the body, and equal but opposed to it. This resistance will be designated by s and is called stress; therefore

$$s = p = P/a \text{ as above. } \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Stress is habitually stated in the United States in lbs. per sq. in.; in Great Britain in tons per sq. in.; and in all other countries as kilograms per sq. cm. or per sq. mm. In the following lbs. per sq. in. will be given, while French measures will be frequently added. As 1 kilo per sq. cm. is practically equal to pressure of 1 atmosphere, this expression, represented by *at.*, will frequently be used.*—G. C. Hg.

* As this book will be published in the United States, where the metric system is unfortunately not in common use, among a population of about 75 millions, the American standard will be used. It is not possible to use the English standard of tons, and it is a misfortune that the metric system cannot be used as is the case in the original.—G. C. Hg.

34. Under effect of stress the body elongates, at the same time reducing its cross-section. The length l_g becomes l_{g1}, and the extension between sections *aa* and *bb* equals

$$e = l_{g1} - l_g$$

The extension of the unit of length shall as a rule be called elongation and be designated by e_1; therefore

$$e_1 = \frac{e}{l_g} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 2$$

It is, however, common practice to state elongation in per cent of gauge length, and this shall in future be indicated as follows:

$$e\% = e_1\, 100 = \frac{e}{l_g}\, 100 = \left(\frac{l_{g1}}{l_g} - 1\right) 100. \quad . \quad . \quad . \quad 3$$

The factor of elongation * is that elongation which the body shows under the unit stress; it is therefore

$$e_f = \frac{e_1}{S} = \frac{e}{l_g} \cdot \frac{1}{S} = \frac{e}{l_g} \cdot \frac{a}{P} \quad . \quad . \quad . \quad . \quad . \quad 4$$

Elongation may therefore be written as the product of stress and factor of elongation:

$$e_1 = e_f.\, S$$

and the extension of a bar of length l_g:

$$e = e_f.\, s\,.\, l_g$$

and the stress in the bar may be found from the fraction, elongation divided by factor of elongation, i.e.,

$$S = \frac{e_1}{e_f}$$

* Considère employs the expression e in common use in France as extension in $m/m.s$, and $e.f$ (*L.* 105, *p.* 10);
he gives for iron $ef = 0.000048$ to 0.000052, and
for steel $ef = 0.000044$ to 0.000048.

The expression $\frac{1}{e_f} = \frac{S}{e_1} = E$ is generally called the Modulus or Coefficient of Elasticity.

35. While the body is extending under the effect of stress, it is at the same time undergoing a diminution of cross sectional dimensions; the original cross-section changes from a to a_1, which is smaller. The body undergoes a reduction of area or contraction, which may be expressed by

$$c_1 = \frac{a_1}{a} \text{ or in \% of original section :}$$

$$c\% = 100\left(1 - \frac{a_1}{a}\right). \quad . \quad . \quad . \quad . \quad . \quad 6$$

36. In order to calculate the stress S with absolute accuracy it would be necessary to refer it momentarily to the new cross-sectional area due to effect of P; still it is habitual to refer it to original sections. This is done as a matter of convenience and is permissible, because deformations in structures are always so small that diminutions of section are hardly noticeable, and on the other hand calculation would become unnecessarily complex if we attempted to carry it out.

It has been repeatedly proposed to calculate ultimate resistance with the fractured section as a basis, but this proposition has not as yet met with any degree of success.* The usual method shall therefore not be departed from except in exceptional cases.

When elongations e_1 of the bar under various stresses S are known, it is possible in case of a material of density $= 1$ to calculate stress S_1 referred to sections a_1 from S and e_1 under the assumption that the bar under consideration changes its volume v to an unim-

* [I think this proposition is totally wrong, because the load at instant of rupture, in case of ductile materials, is mainly dependent upon time and upon the apparatus used. The fractured section is furthermore frequently so indefinite and dependent upon local conditions that its use as a basis for calculations is hardly admissible.—G. C. Hg.]

portant extent during deformation. Under this assumption, for the section of bar of length l_g.

$$l_g.f = v = (l_g. + e_1)a_1;$$

therefore for the unit of length

$$a_1 = a(1 + e_1)$$

and as

$$S_1 = S\frac{a}{a_1},$$

$$S_1 = S(1 + e_1).$$

As e_1, to be shown further on (Chap. VII), stands for the average elongation of gauge length l_g, it is more accurate to say that stress s_1 must be referred to a mean cross-section of the strained * body. When it is desired to refer it to the smallest section this cannot be done, but by making direct measurements of reduced cross-sections when the % of reduction $c\%$ is determined from one test, equation 6 gives

$$C\% = 100\left(1 - \frac{a_1}{a}\right)$$

$$a_1 = a\left(1 - \frac{C\%}{100}\right),$$

and as

$$S_1 = S\frac{a}{a_1},$$

$$S_1 = \frac{S}{1 - \frac{C\%}{100}}.$$

Knowing the reduction of section $c\%$, we can easily calculate the relative extension e referred to the minimum section a_1, as follows :

As

$$C\%.a = a(1 + e_c),$$

$$C\% = 100\left(1 - \frac{a/(1 + e_c)}{a}\right) = 100 - \frac{100}{1 - e_c}$$

$$e = \frac{100}{100 - c} - 1.$$

Fig. 4 is a diagram of relative values of $c\%$, $e\%_c$, and e_c.

---

* The word "strain" is used as in Rankine, and shall invariably apply to change of length due to forces applied.—G. C. Hg.

In addition we must consider the relation between stress and strain existing in a long prismatic body under increasing loads, carried to the maximum resistance and ultimate failure.

37. Experience teaches that in many materials of construction the property of approximate proportionality between stress and strain is constant up to a certain degree of the former, or that strain is proportional to stress:

$$\left.\begin{aligned} e_f &= e_1/S = \text{constant; hence} \\ e_f &= \frac{\Delta e_1}{\Delta S} = \text{constant;} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad 7$$

The proportion between increment of strain and of increment of stress is constant.

When stress S is further increased, the factor of elongation (strain) is changed; it increases in most materials. That stress, at which the strain ceases to increase proportionately to it, is called the proportional limit; it will hereafter be invariably indicated by adding the suffix P to the symbols $S, e, e_1, e\%$, etc., which will read: $S_P, e_P, e_{1P}\, e\%_P$, etc.

Materials in which e_f is variable for all loads, such as cast iron, magnesium, etc, have no proportional limit, or, for short, lack the P-limit.

It is to be regretted that there is no short name for this point. It must further be remembered that this limit, in common with all other similar points, cannot designate a well-defined instant, because changes of condition of material are constant during tests. Moreover, our present means of investigation do not permit us to decide whether strict proportionality exists or not, and although I am inclined to deny it, I do not wish to discard the present general belief. Therefore it must not be overlooked that the P-limit is a conventionality, and that its location always depends upon the delicacy of the apparatus, as shall be shown hereafter, and also upon the habits and views of the observer.

38. For our further examination we shall assume a material, such as iron, which has a definite P-limit. The occurrences may be shown by a diagram, in which stresses S are laid off as ordinates and strains as abscissæ, as shown in Fig. 5. Proportionality obtains up to the point P. The line $\overline{OP}$ is

straight, changing with gradual curvature from P to Y. From Y the extensions e_1 increase much more rapidly than stress S (sometimes suddenly); the bar yields or flows. P is the proportional limit, and Y is called the yield-point. The yield-point is that stress at which, under uniform increment of loads, the extensions increase rapidly. Up to this point the extensions were relatively minute, so that they are recorded on a very much magnified scale, to define them clearly in Fig. 5.

It is readily noticeable, and daily experience teaches, that the Y-point, as also the P-limit, are well-defined points. There are numerous methods in common use to determine their position, and these, as will be shown, give varying results.

39. In producing further extensions (always referred to original sections) stress S is increased.

Its growth becomes gradually less (in iron!) until S reaches a maximum value, after which it again decreases to the instant of rupture. Recording this on a similar diagram of smaller scale, we obtain Fig. 6. Points P and Y are the same as before. Stress at point M is called maximum stress, S_M; stress at point R is called rupture-stress, S_R. The relative elongations are e_P, e_Y, e_M and e_R, and these will be referred to later on.

40. It is sometimes easier to refer to loads and extensions than to stresses S and strains e produced by them respectively, and to draw diagrams with these. It will readily be seen that the diagrams will be similar, as stress with constant section is calculated from L, and the elongations with l_r constant. Testing machines are frequently provided with (Automatic Recorders) apparatus for drawing diagrams as above explained, recording according to L and $e\%$ automatically.

It is of course more usual to make diagrams referred to L and $e\%$, and I should have proceeded likewise for simplicity's sake, but the advantages of reference to S and $e\%$

will be quickly recognized, when it is considered that diagrams drawn on identical bases will always give curves of tests more or less incident throughout, for the same material. One glance shows all the characteristics of the material and makes mental comparison with the average curve, carried in mind, very easy. For this reason I have adopted definite scales* for diagrams in the students' experimental work, and it is not at all difficult to draw the diagrams directly, by use of the slide rule, from the test reports, for values of S and using the trick of observing the extensions in % of l_g, as e% either a decimal multiple of l_g is used or other scales are divided in percentual parts of various test lengths, as will be more fully explained in (137). Indeed there is very little difficulty to so arrange a testing machine that stress s is indicated by or read off from the testing machine instead of loads, even while using test pieces of various sections. This can be done in a number of ways, and would be by no means impractical, especially as most of them are used for only one kind of test. I shall again return to this point at the end of the book.

41. Thus far uniform increment of stress was imagined and the consequent elongations recorded. When the procedure is, however, changed, so that the stress after reaching definite intervals is released, i.e. when a bar loaded by a force L is relieved† until $L = O$, we obtain in case of material with decided P-limit, like our iron sample, a diagram such as is shown in Fig. 7.

In the beginning the body loses the elongation e, upon release from stress S, entirely. The body assumes its original shape completely, it is perfectly elastic. When unloading after successively increasing stress, the body will from a certain limit fail to regain its original shape perfectly, a re-

* I use rectangular co-ordinates making $s = 1000$ at. equal to $e = 0.100$; or about 5000 lbs. per in. equal to actual extension.

† In relieving loads, the remarks contained in Chapter 12, section 314a, must be noted.

sidual change will be noted, which does not disappear, the *permanent elongation or permanent set.* This point or limit is called the *Elastic Limit* of the material; i.e., *that stress at which the body assumes permanent deformations.* It is a common belief that elastic limit and P-limit coincide; however, there is no conclusive reason for this assumption, as will be shown hereafter; it certainly still requires exhaustive examination. The elastic limit shall hereafter be designated by E_l; hence:

$$S_{E_l} \text{ and } \epsilon_{E_l}.$$

This is the proper place to call attention to a *very important misconception* which is produced by the uncertainty of accurate definition of the idea of elastic limit, and the existing careless distinction between proportional and elastic limits and of yield point.

This uncertainty is by no means due to the fact that these limits have in themselves no precise or definite location, but are determined only approximately by the relation between S and E; it has rather been caused in particular by the indiscriminate substitution of S_P for S_{El} or the reverse, and still more by the determination of the S_Y or Y point, instead of the others, *while actually making tests.* In practice, what we call *yield-point* Y point *is frequently called Elastic Limit* E_l, without any indication how it has been determined or what is intended thereby. It is frequently possible to determine the true import of reports only by the relative location of the maximum load. Sometimes it is possible, knowing the habit of an entire country, to interpret reports, and then only when relating to one group of material, and to know what is meant by the term "elastic limit." It may be assumed, for instance, that when the term is found in German papers by practicing engineers the yield-point is as a rule referred to. The same may similarly be assumed in English and American papers; but with the French there is frequently doubt, because they often really mean S_{El}, when speaking of elastic limit. This is indeed a serious matter; for this carelessness in diction may easily lead to a change of opinion of the qualities of material by transposition of these limits, and actual injury may sometimes be done.

The matter obtains direct importance when testifying as an expert in court, as to whether S_{El}, S_P, or even S_Y were intended when the term elastic limit is used in a contract. I cannot dwell upon this point with too great frequency or too much insistence, and impress the necessity and importance of using these terms with greatest accuracy and precision, in order that authors, not for them-

selves, but for their readers and students who take pleasure and enjoyment out of a publication may have their labors facilitated.

[TRANSLATOR'S NOTE. The frequent and rather sharp discussions of these terms had in many technical journals, show how important precision in the use of technical terms really is. It may be stated, however, that as a general rule, those who maintain that the term "elastic limit" is more correct then "yield-point" have failed to study the subject with that profundity or scientific accuracy and patience which alone entitles their opinions to be considered authoritative. It is an unfortunate fact that in the U. S. many so-called "inspectors" are not scientifically trained, and have not had the necessary laboratory training which would make them competent critics, although the discussion was sustained by such. It will appear from the previous discussions in the text that the terms, proportional limit, elastic limit and yield-point each represents definite distinct scientific ideas of properties of materials, which may or may not each or all of them co-exist in any one material. In structural steel all three are readily located by proper methods; in annealed tool steel likewise; in hardened tool steel there is no yield-point, any more than in most cast irons.

In cast iron there is no proportional limit, because every load produces set, while cast iron has a yield-point; those, however, who always work by drop of the beam would deny this, because the beam gives no indication of it, any more than in the case of tool steel. G. C. Hg.]

42. As soon as the stress rises above the elastic limit S_{E_l}, that is, to the point A or A_1, Fig. 7, we shall find upon release from stress that elongation of e_A returns to point e'_A. This part e'_A of the total elongation e_A is the residual elongation, called permanent set, while $e_A - e'_A$ is the elastic elongation or resilient extension. In a diagram drawn with ordinates representing L and e, e' represents permanent set, and the elastic extension $e - e'$ is resilient tension. When resilient extension and permanent set for each stress S are plotted on Fig. 7, the finely broken line is obtained, which is marked at its upper end by e'; thus the diagram makes the entire elastic behavior of the material during tension test apparent.

43. While the body is changing its length under constantly increasing stress in accordance with laws now known, it also changes its cross-section. In this change elastic and permanent changes may be observed, as was the case in

changes of length. Experience teaches that elastic changes of length and section are also related in a certain measure.

Within the proportional and elastic limits (P and E_l) this proportion is given by the relation of contraction C to e_1 elongation:

$$C = e_1 \frac{1}{m}, \text{ or}$$

elongation to contraction:

$$C_l = e_l \frac{1}{m},$$

in which m is a constant which, derived from numerous tests, lies between 3 and 4; i.e., the *contraction produced by definite stress is equal to from $\frac{1}{3}$ to $\frac{1}{4}$ of the elongation coincident with it.*

Under these conditions, within elastic limit a change of volume of test-piece would be coincident with variations of $e_1 - c_1 = e_1 \frac{1}{m}$, which for the unit of volume is obtained from

$$V_1 = (1 - c)^2(1 + e_1) - 1,$$

or

$$V_1 = \left(1 - \frac{1}{m} e\right)^2 (1 + e_1) - 1.$$

44. Permanent change of shape occurs, as explained in (*25*), in such manner in case of materials of density $= 1$ that the volume remains nearly constant. While, however, the contraction within the E_l and P limits, in case of a prismatic bar (thus far alone considered), and immediately after passing them, is quite uniform over the entire length under observation, further stress produces a condition under which local diminution of section occurs. One or several *contractions*, Fig. 8, occur (in soft material—still speaking of

iron), and finally rupture takes place at or near the least dimension of such contraction.

45. The beginning of this contraction leading to rupture almost coincides with the maximum load S_M for diagrams Figs. 5 and 6, from which it follows that stress S decreases, as well as the load L, during further extension.

Practically this means, for the case under consideration (iron), that the maximum load (Fig. 6, M) would undoubtedly cause rupture of the bar if its particular structure permitted free extension up to the instant of rupture—if, e.g., the load L_M hangs on the bar. Testing-machines sometimes also permit the determination of the ultimate or load at rupture L_R, which is carried by the bar at the instant preceding rupture. The knowledge of this load L_R and the stress S_R produced in the bar is of practical utility only in very few cases, and hence it has been agreed to use the *maximum load* L_M *or stress* S_M *as the basis of calculation of tensile strength of the material*; it is sometimes called *ultimate load* or *ultimate stress*.

46. *Tensile strength, permanent extension after rupture* and *reduction of area, contraction of ruptured surface* are generally used as *principal measures* of *quality* of materials of construction. Sometimes the P and Y limits are also considered. For the constructor the P limit and factor of elongation, e_p, within this limit are undoubtedly of the greatest importance, even though their accurate determination is difficult (37, 38).

47. Habit and the Resolutions of Conferences for Unification of Methods of Testing have established the custom of stating the elongation after rupture $e_R\%$ with the maximum stress S_M, instead of the elongation at that instant $e_M\%$. The practical reason for this is to be found in the difficulty of accurately determining with precision the elongation at maximum stress $e_M\%$ with existing apparatus or from plotted

diagrams (or even from autographic diagrams). This is easily understood by reference to Fig. 6, a diagram of iron, in which the curve near maximum stress at M is nearly horizontal.

The elongation after rupture is generally expressed in % referred to an original standard of length, which will be most fully discussed in Chapter VII. Hereafter it will always be termed elongation, and indicated by symbol $e\%$.

The symbols S_P, S_Y, S_M, $e\%$, and $c\%$ shall represent those results of tension tests which characterize the qualities of materials in the eyes of the investigator.

48. Remembering that stress is that part of the load carried by the unit section, and that unit extension denotes a distance traversed, namely of the end section of test-piece of $l = 1$ due to stress S, we may say that the work done and resisting extension is equal to the product of stress by extension.

From these factors S and e_f we shall have the specific work A_f with which the unit of volume of material resists change of shape:

$$A_f = \Sigma S \,.\, e_f.$$

Calculating from L and e load and extension produced thereby, we shall obtain as the work done by the entire bar of length l_g during resistance to deformation

$$A = \Sigma L \,.\, e.$$

Diagrams give at every instant the stress S or load L for the corresponding $e\%$ or e_1, and by summation of these values can readily give the specific work or resiliency ΣA_f or ΣA.

In the stress-strain diagram Fig. 9 the area of triangle $OPe\%_P$ represents the sum of specific work done, up to the P limit, or the elastic resilience; it is

$$A_l = \tfrac{1}{2} S_P \,.\, e_P. \qquad \ldots \ldots \quad 8$$

Others have followed this idea to a greater limit, as H. Fischer, Hartig (L 106) and others, but I do not wish to continue it because my extended experience of and occupation with testing and its practical applications have convinced me that the matter must not be complicated more than is absolutely necessary. As I am writing this book primarily for its practical applicability, I must refrain from a more detailed discussion of the subject, and also in such cases which appear interesting and of scientific value to me; I would therefore protect myself at this place against the accusation that I neglected this subject.

Bodies by no means cease to be elastic after passing the P-limit; on the contrary, the resilience may increase even to the instant of rupture. Hence they exert elastic resiliency, even though permanent deformations are occurring. The amount of this work can, of course, be determined by repetitive unloading tests up to the instant of rupture, but in doing this, as shall be shown later on, most materials suffer a material change of condition, the magnitude of which depends upon manifold conditions of the test.

Fischer represents the total resiliency A_e' by a diagram with co-ordinates of S and e_1. From this he develops the conception of degree of elasticity, as the relation between specific elastic resiliency A_e' and the specific resiliency A_f; or $= \frac{A_e'}{A_f}$.

Specific elastic resiliency A_e' is divided by Fischer into two parts, A_e'' and A_e''', or into the resiliency during elastic deformation and of that, after passing the elastic limit. But in this we must also remember that Fischer's elastic limit corresponds approximately to our Y point. He furthermore uses the proportion $x = \frac{A_e'''}{A_e''}$ to represent properties of materials. Were we to follow his proposition, otherwise noteworthy, it would materially complicate the art of testing materials (*314*).

49. The work of resistance, resiliency, to be done up to the Y point and maximum load (Fig. 9) are represented by the areas $OPYMe_YO$ and $OPYMe_MO$. That part of the resiliency overcome beyond the maximum load is of no consequence to the constructor, as previously indicated. It may, however, be of great value to the technologist under certain conditions, and hence cannot be neglected; it is measured by e_MMFe_F.

The entire hatched (Fig. 9) area of diagram is a measure of resiliency, which the unit of volume of the material in question can oppose to rupture. It must not be forgotten, however, that this is not strictly

correct in case of soft materials, which suffer local contraction and hence give a line which drops from M to R, for the section 3 is produced only by that part of the bar at which local contraction occurs. Therefore it is customary to neglect this drop of curve when calculating ΣA, and to add the corner 4 in full.

The resiliency A is sometimes also recommended as a measure of quality of materials.

50. When a diagram is available it is easy to determine its area by calculation, by planimeter or by weighing the diagram, cutting it out along the curve and the base and final ordinate.

In order to elucidate the use of instruments, their sources of error and the determination thereof, and to give my students opportunity of doing independent work, they must make such calculations, measurements, and weighing. If practical accuracy suffices, then merely counting the squares of cross-section paper covered by the curve will give the result rapidly, as is shown by the following example (Fig. 10), in which the curve is considered as covering rectangles, as many squares of which lie within as others lie without it. Eye measure is sufficient for this. An easy calculation then gives:

Circumscribed rectangle $A_1 = 3740 \times 0.380 = 1421$

Surface 1	—	2600 × 0.380	=	988
" 2	—	800 × 0.320	=	256
" 3	—	340 × 0.170	=	58
				1302

and
$$\frac{\Sigma A_f}{A_1} = \frac{1302}{1421} = 0.92$$

51. It is, however, not customary to obtain an autographic diagram; in fact the trouble is rarely ever taken to determine values of P_f e, S, and e_1 during the test. It is

nevertheless possible to determine the resiliency with reasonable accuracy from the data usually observed in a test.

We are helped in this by our experience that the relation between the area of the diagram of resilience and that of the circumscribed rectangle can be expressed by a number, which varies only in a very slight measure. The area of the rectangle is always given by the product, derived from the test:

$$A_1 = S_M \cdot e_R$$

or maximum stress by ultimate elongation.

The ratio between the area of diagram ΣA and of the circumscribed rectangle is called the equality-ratio of diagram of resiliency; it is always less than 1 and in future shall be denominated by

$$E_q = \frac{\Sigma A_f}{A_1}. \quad . \quad . \quad . \quad . \quad . \quad . \quad 9$$

Hence the resiliency of any material may be obtained from maximum stress, ultimate extension and equality-ratio, or:

$$\Sigma A_f = S_M . E_R . e_q. \quad . \quad . \quad . \quad . \quad . \quad 10$$

This value is given in German works in cm kc/ccm, and in English in inch-pounds (in. lbs.).

In German the resiliency is often based on 1 gramme instead of 1 ccm; and it then becomes

$$\Sigma A_f = S_M . e_R . E_q \frac{1 \text{ cm kg}}{g}, \quad . \quad . \quad . \quad 10a$$

as 1 ccm of solid material weighs Sp. Gr. $\times$ g.

52. In order to obtain an exhaustive illustration of the behavior of material during the tension-test we must revert to a case previously discussed, viz., the case of repeated loading and unloading. For this purpose a bar of magnesium is

to be considered instead of one of steel, because it shows the properties under discussion, the residuary or resilient phenomena, to a marked degree.

53. When a body is loaded rapidly but without shock, so that it is not subject to longitudinal vibrations, it does not at once assume entirely the length due to its properties and the loads applied. When allowed to rest after loading it will change its length under the influence of the load, for seconds, minutes, even for days and weeks.

A very similar case is found to exist when the load is removed and the body is allowed to rest without effect of the load; it shortens in course of time.

The phenomena of change of shape in course of time are called residuary or resilient phenomena. These phenomena are as a rule unobserved, because in many materials they can be determined only by means of very delicate measuring-instruments; in some, e.g. rolled magnesium, they are more apparent, so that they can be readily determined with the ordinary instruments of precision.

In the following is given a general review of these phenomena (Fig. 11) based on an actual test (*L 107*).

While loading up to the point A a steadily curved line is recorded, because the rolled magnesium test-piece does not show a proportional limit (P-limit). Upon maintaining the stress at A for, say, 5 minutes, the bar continues elongating; in the test mentioned a residuary extension ϵ'', of .0002925 in., took place under a stress of 1270 at. The amount of this residuary extension is indicated by the heavy horizontal line. Upon increasing the stress after 5 minutes' delay to the point B, and a further lapse of 5 min., the same effect takes place, which will again occur at C, the residuary extension ϵ'' in equal intervals of time will be found to be greater at B than at A, and greater at C than at B; similarly, the residuary extension at F, G, and H constantly increases.

By observations during successive minutes the law governing this residuary extension can be comprehensively represented by plotting it and the corresponding stresses on a diagram with rectangular co-ordinates. The diagram e'', 1, 2, . . . 5, etc., is thus obtained (*L 108*, *1887*, p. *72*).

When the stress at points E or J is reduced to, say, 80 at., the extension decreases on broken lines to D or H, and in course of time further contractions take place to amounts shown by heavy horizontal lines. This contraction may again be plotted the same as the extension; the broken curved line to the left of the vertical through the origin is thus obtained.

As previously stated, these residuary extensions and contractions are minute. Table 4 gives these values for a bar of magnesium.

Table 4. **Residuary Phenomena of Magnesium.**

S in at.	e_1 in $\frac{1}{100000}$ cm (= cm 10^{-5}) after Minutes					e_1 cm 10^{-5}
	1	2	3	4	5	
1270	16	29	37	44	50	385
1350	20	29	36	46	51	417
1430	19	30	50	55	69	450
80	− 4	− 10	− 11	− 13	− 16	98
1430	33	51	61	72	77	464
1510	33	51	59	77	85	502
1590	47	72	107	114	132	548
80	− 11	− 17	− 28	− 31	− 34	158
1590	23	47	66	83	97	577
1670	30	63	95	125	137	628

I have most fully treated these phenomena as referring to magnesium in a separate publication (*L 107*). Besides this I have repeatedly called attention to similar occurrences in other materials in the " Mittheilungen " (*L 109* and *110*). I

append a few additional remarks about the study of these phenomena in case of magnesium, which are intended to show to what extent they deserve our attention.

The effect of residuary contraction may be recognized even after repeated extension due to re-application of stress (see p. 44), just as the residuary extension may be of influence upon the degree of residuary contraction upon release of stress. In other words, the effect of any stress on material does not immediately cease with its removal, but it also affects the resultant phenomena of later and opposite stress. Our Past Master Bauschinger has repeatedly called attention (*L 111*) to similar phenomena depending upon time, which are partly to be considered further on (Sect. 313).

The effect of initial treatment is readily recognized upon making a test, say a tension-test, one by successive intermittent stress without release and a second with similar material, with release of stress in 3 or 4 intervals. In the first case a constant increase in the successive extensions will be noted, while in the second, the period following release of stress will show a difference relatively too small, caused by the contraction occurring during release (p. 69 of *L 110*). These occurrences, to speak figuratively, act like waves upon water, often plainly visible and crossing each other according to fixed laws. In degree the last stress applied has the most important effect upon the phenomena, while the effects of stresses previously applied are greatly modified, and gradually disappear.

Such occurrences have moreover been frequently demonstrated heretofore. E. Warburg reports:

"In the case of copper the time of vibration (in case of suspended wires subject to torsional vibration) is dependent upon the interval of time elapsed since the last previous change of stress, and in fact decreasing with increase of time, whether the stress had been either increased or decreased. Pisati and P. M. Schmidt have shown the same to occur in various metals."—"If a copper wire be strained

under a certain permanent torsion and be also loaded by tension, it loses permanently, as Wiedemann has shown, a part of its permanent torsion; during a subsequent removal of load, the decreased torsion remains or is still further decreased. Repeated loading and release operates in the same manner with decreasing intensity, and finally the wire attains such a condition in which a lasting change of permanent torsion is no longer produced by loading and release."

Similar tests of other investigators have shown that the origin of vibrations under torsional vibrations of wire is shifted in the direction of the first stress, that under opposite stress it returns in a similar direction, and also that the direction of the previous stresses exerts influence on the magnitude of the effect of those applied later. When the results of tests recently published by Bach, Hartig, and others, of mortars, concrete, leather and other materials, are compared with the previous, the mass of interesting conditions becoming practically valuable, which may be developed by further study, cannot remain concealed. (*L 112.*)

54. It will be seen from the foregoing presentation that the residuary phenomena above discussed, interesting as their study in themselves may be, and although they may be much considered in future tests of material, are not, as a rule, of material importance for the constructor. They are on one hand very minute, generally even much smaller than in the case of magnesium, and on the other become apparent, mainly under such stresses which lie above those allowable in construction. For the accurate knowledge of properties of materials their study of course retains its importance.

There are, however, further residuary phenomena which occur at stress below the E_l limit, the elastic residuary phenomena. Their study is only possible by use of the most delicate resources of the physical laboratory, and no doubt belongs to the most interesting field of natural sciences, but is of no immediate value for the constructor, and therefore further discussion of the subject is dropped.

Resistance to Crushing.

55. The relations and ideas in the crushing-test are very similar to those of the tension-test; only the forces must be considered as acting in a reversed direction.

In Fig. 12 a very long prismatic bar is assumed, on the selected section *aa*, *bb*, of which forces $-P$ act compressively in the axis of the bar. Instead of extension e in the tension-test, the material is shortened $-e$, and instead of contraction of area, increase of section takes place. The relations between forces, stress, and deformations are similar to those under tensional loads; using the previous notation with negative prefixes, these relations may be expressed as below. The load in any section of area $= a$ of the prismatic body will be

$$-p = \frac{-L}{a}, \text{ or}$$

the stress:

$$-S = -p = \frac{-L}{a}.$$

The amount of c r u s h i n g, or u p s e t t i n g, which the body undergoes under the crushing stress is

$$-e = l_{\varepsilon_1} - l_{\varepsilon}.$$

The c r u s h i n g of the unit length, or c r u s h i n g r a t i o, is:

$$-e_1 = \frac{-e}{l_\varepsilon}, \text{ or}$$

in per cent of original length:

$$-e\% = -e_1 100 = \frac{-e}{l_\varepsilon}100 = \left(\frac{l_{\varepsilon_1}}{l_\varepsilon} - 1\right)100.$$

The crushing factor $-e_f$, i.e., the upsetting ratio under the unit load, is

$$-e_f = \frac{-e_1}{-S} = \frac{-e}{l_g} \cdot \frac{1}{-S} = \frac{-e}{l_g} \cdot \frac{a}{-L}.$$

Again as before, we may write:

$$-e_1 = e_f - S, \text{ and}$$

for the upsetting of a bar of length l_g:

$$-e = e_f . - S . l_g, \text{ and}$$

for the stress:

$$-S = \frac{-e_1}{e_f}.$$

The Modulus of Elasticity for crushing is therefore

$$\frac{1}{e} = \frac{-S}{-e_1} = E_c.$$

The increase of section upsetting produced under the effect of crushing stress may be represented by

$$-c_1 = \frac{a_1}{a}, \text{ or}$$

in % of original sectional area:

$$-c\% = \left(\frac{a_1}{a} - 1\right)100.$$

When it is desirable to express the stress, as in par. 36 for tension, referred to the actual section instantly produced by it, i.e., to the cross-sectional area of a prismatic body, the volume of which is equal to the crushed and upset test-piece actually used, the formula

$S_1 = S(1 - e_1)$ applies directly.

56. In the crushing-test the upsetting or crushing in many materials is again at first proportional to the stress; they therefore have a proportional limit for crushing loads (S_{-L}); up to that point:

$$-\epsilon_f = \frac{-\epsilon_1}{-S} = \text{constant}; \text{ and also } -\epsilon_f = \frac{-\Delta\epsilon_1}{-\Delta s} = \text{cons.}$$

The proportion between upsetting and increase of stress is uniform.

Plotting a diagram for iron, a material having a clearly defined $-P$-limit, supplementing it by the tension diagram, so that the stress and changes of length are laid off on opposite sides of the axis, we shall obtain a representation as in Fig. 13.

The proportional limit is found at $-S_P$, where the curve begins to deviate from a straight line. When the changes of length are equal in tension and crushing tests, the part—POP will be a right line. The yield-point for crushing-loads is more or less well defined; it is called the upsetting limit at $(-S_Y)$. The crushing-point $(-B)$ is clearly marked only in brittle materials, such as cast iron, stone, cement, etc., while tough and ductile bodies, such as lead, copper, low steels, etc., cannot be ruptured, as they suffer extraordinarily large changes of shape under crushing-loads without the appearance of signs of rupture. In such materials the pressure may be increased very largely without producing rupture, as is shown by the broken line part of the diagram Fig. 13.

The preceding conclusions are derived from current considerations and experience, which actually always refer only to bodies whose relation of length to section is very limited. Because of more ready representation in connection with deference to daily experience, the short test-piece has been quietly referred to. It is in fact very difficult to make a crushing-test of long bars so as to prevent all secondary effects of stress. In this case the relations wouid probably be somewhat modified, in so far as bulging of the crushed

bodies would in case of long test-pieces be local, similar to contraction of the tension test-piece.

57. In case of test-pieces which are not ruptured by crushing, the maximum load S_{-M} cannot be used as a measure of quality of the material, because it is not characteristic, but depends upon the fact as to how far the test had been actually carried. It is in most cases sufficient for the constructor to know the upsetting (yield) point at which the material begins to yield materially. As a *measure of quality* for *tough materials* this *upsetting* (or *yield*) *point must be used*, *while it is customary to use the crushing-load* for *brittle materials*. These measures are therefore not directly comparable; each is applicable in its special field only.

58. In case of elastic materials, the elastic property itself becomes pronounced in crushing-tests. In this case also there is a part which returns to its initial condition. Accordingly distinction is made between *elastic* and *permanent crushing*; *crushing-set* and resiliency are noted. As in the tension-test, *residuary phenomena* become apparent.

59. Similarly to contraction in tension test-pieces, there is bulging or upsetting governed by similar laws; within the elastic limit

$$c = -e_1\frac{1}{m} \text{ is true; or}$$

$$c_f = e_f\,\frac{1}{m},$$

in which m is a number which general experience shows to lie between 3 and 4, and which may be considered identical for tension and crushing in the same material.

Permanent deformations of material of density 1 during crushing-test occur as in the tension-test, in such manner that the volume of the body remains nearly constant under all deformations.

60. The work done or resilience with which a body resists deformations can be deduced from the product of stress and crushing produced thereby, as in the tension-test. The specific work A_f which the unit of volume opposes to deformation is:

$$A_f = \Sigma s . - e_1.$$

The total work done can again be determined from the diagram.

The area of triangle $O, - P, e_{-P}$, Fig. 13, is the sum of the specific work done up to the $-P$-limit or the elastic resilience:

$$A_{f-P} = \tfrac{1}{2} . S_{-P} . e_{-P}.$$

The work done up to the upsetting or yield point $- Y$, or up to the crushing-point $- M$, in resisting stress is given by areas $O, - P, - Y, e_S, O$; or by $O, - P, - Y, - M, e_M, O$, Fig. 13. That part beyond the yield or upsetting point has relatively little value for the constructor, as previously elucidated; only in case of bodies actually fractured a definite value of resilience is characteristic. The technologist, however, will not neglect without further concern that part beyond $- Y$, because it gives valuable points as to the workability of the material in many cases.

2. Character of Testing-Machines and of Measuring-Apparatus.

61. Thus far the behavior of a very long bar subjected to tension or crushing test has been considered. In actually making tests the bar must be held or gripped by the testing-machine in a suitable manner. Because this circumstance, as well as the method and arrangement of the machine used for the tests, exercises a certain influence on the results, it is now necessary to consider the principal features of machines and holders or grips. For

the same reason it becomes necessary to give a general review of the character of measuring-apparatus at this time, although special consideration of these matters and of methods of testing will be relegated to the final chapters of the book.

As only general considerations of making tests are here described, which are to serve as a starting-point for the discussion of effects of method on results of tests, the descriptions here given are only schematic, reserving detail for later chapters.

a. Testing-machines.

62. A testing-machine generally consists of three principal parts:

A) Driving or loading mechanism; generally screw gearing or a hydraulic press;

B) Load-indicator, generally lever, hydrostatic or spring balance;

C) Frame, support, or base.

It is the province of the loading mechanism to transmit loads to the test-piece, producing in it stress S.

The object of load-indicator is to indicate or measure the loads applied with sufficient accuracy.

The purpose of the frame or support is to transfer the loads transmitted by the test-piece to the loading mechanism, thereby closing the circuit of forces.

63. The test-piece must be introduced between loading mechanism and load-indicator. For this object they are provided with holders, grips, or jaws, which grip the ends of the test-pieces.

64. The desire for brevity of expression and the desire of describing essentials or typical construction of groups of machines led me years ago to introduce schematic or diagrammatic notation (*L 113*), which I shall retain here, as long as detail is not to be discussed. This notation is as follows:

Fig. 14 refers to types of driving mechanism; *a* indicates a screw-press, *b–d* hydraulic presses, *b* with plunger, *c* single-acting, *d* double-acting.

65. Only the typical designs of various construction of load-indicators will be here mentioned in essential characteristics, with diagrammatic notation as in Figs. 15 to 22.

Two principal groups can be defined, one in which the loads L transmitted by test-piece are measured intermittently (in intervals), and the other in which these loads are measured steadily or constantly.

In the first group the moment $Pa = pb$, Figs. 15 and 16, grows in intervals or intermittently: two principal types may be distinguished:

65a. Lever-scale (steelyard), Fig. 15 (two-armed, single-arm, angle-lever). The lever ratio a/b is constant; load p is variable; balance-weights applied by hand (the lever-balance is used in the Werder, Rudeloff, and Mohr and Federhaff machines).

65b. Lever-balance (steelyard) with mechanical deposition of weights, Fig. 16. The weights p are changeable in intervals, lever ratio a/b remaining constant (such arrangements are found in the Emery, Gollner, and Martens machines).

Weights (discs) p are deposited by mechanism, which generally has a reciprocating motion (indicated by the double-headed arrow shown). Hatched parts invariably indicate fixed points, such as bearings, guides, etc., rigidly connected to the frame or base of machine. Devices of the second kind usually have the advantage of depositing weights without impact, thus avoiding the transmission of heavy shock or impact upon the test-piece; it is also more certain to avoid errors of counting weights deposited. Unloading is also much more readily done than in the first case. It is, however, necessary, in order to avoid great complication when using small increments of load in case *b*, to provide smaller

weights in addition. In case of second group of load-indicators a constant increase of load P is obtained; this can be done in several ways.

65c. Travelling poise steelyard, Fig. 17. In this case a and p remain constant and the lever ratio a/b changes. The poise can be operated by hand so as to produce either intermittently increasing loads (as in cases a and b) or uniform increase, maintaining equilibrium. This is, however, frequently achieved by a great variety of mechanism, operated automatically by the machine. In this case the machine generally acts as a relay, to throw the poise mechanism in and out of gear (Riehlé, Olsen, Wicksteed, Martens, Morgan).

65d. Pendulum-balance, Fig. 18. In this type p remains constant while a_1 and b_1 are variable, the latter referring to the so-called lever-arms of P and p.

Assuming the notation given in Fig. 8 as understood, the law of the pendulum-balance may be briefly stated as follows:

$$Pa_1 = pb_1; \quad a_1 = a \cos \phi; \quad b_1 = b \sin \phi.$$

$$P = p\frac{b_1}{a_1} = p\frac{b \sin \phi}{a \cos \phi} = p\frac{b}{a} \tan \phi.$$

$$\tan \phi = \frac{Pa}{pb} = \frac{n}{m}, \text{ or}$$

$$P = n\left(\frac{pb}{ma}\right), \text{ or, abbreviated, } P = na.$$

The rise n, measured on a straight line at a distance m from the lever-axis, is therefore the measure of load on the test-piece. It will be seen that m may be so chosen as to vary the constants of the machine at will. Thus it is easy to obtain, what was stated in Section 40, a measure of loads applied which will indicate directly the stress carried by test-pieces of various sections. It is, however, also possible to

indicate loads on a magnified scale, or even to change it alternately to different ratios. (The Pendulum-balance is found in the Thurston, Pohlmeyer, v. Tarnogrocki, and Schopper machines.)

65e. Spring-balance, Fig. 19. In spring-balances the elastic resistance of springs is used to produce the variable force p, which is generally equal to P, because it usually acts directly on the spring. The traverse of the free end of the spring, its change of shape, serves as a measure of force p or load P. Spring-balances are used almost exclusively for very small stresses, because large springs have very small amplitudes and the errors become too large. (Spring-balances are in use in numerous early forms of so-called dynamometers, dasymeters, etc., in machines used for testing paper, textile fabrics, wire, etc., as in the apparatus of Hartig-Reusch, Wendler, Martens.)

65f. Hydrostatic balances, Figs. 20 and 21. In these scales the force p is measured by the pressure of a column of liquid, the altitude of which is its measure, as well as of the force P. Its transmission and multiplication of p to P is also usually produced by hydraulic means. It may suffice to mention two types of such load-indicators at this time.

In both cases the load P acts directly, or indirectly by a lever system, on the piston (cover) of a vessel, the liquid in which is generally in communication with a mercury-column. In one type, Fig. 20, the mercury rises in a stationary tube (machines of Amsler-Laffon, Chauvin & Marin Darbel, Maillard, Emery*). The rise h of the

* I cannot agree with the author that the Emery type belongs to this group, as it has neither mercury-column nor moving liquid in the above sense. In the Emery there is a transmission of pressures and not of liquid; any amount of increase of pressure will not produce or permit transfer or motion of liquid, except as is made possible by the expansion of the hydraulic chambers and tubes containing it. The pressures transmitted are instantly balanced by greatly reduced forces produced by small weights, deposited mechanically by hand, through a lever system on the plunger or cover of the hydraulic chamber.—G. C. Hg.

column is the measure for P. In the other type, Fig. 21, the mercury-chamber is raised until the indicator shows that equilibrium has been established. The rise h is the measure for P.

It is given by

$$P = \frac{h}{76} \cdot F \text{ (French)} \quad \text{or} \quad L = \frac{h}{30} A \text{ (U. S. Standard)},$$

in which P and L are the load, h = height of column, 76 cm and 30 in. relatively (French and American height of standard mercurial column at sea-level), and F and A are the area of surface of plunger resting on mercury (M a r t e n s machine).

65g. S p r i n g-g a u g e s, Fig. 22. Instead of mercurial, spring-gauges may be used, producing a construction in which the principle stated under *e* is used, only with the difference that instead of direct application of load P, it is transmitted hydraulically.

This method of measuring loads is in general use. In testing-machines it is used on the largest machines ever constructed, those at Phœnixville and Athens, Pa. (It is used in the old S e l l e r s and W h i t w o r t h, and N a p o l i, and M a r t e n s oil testing-machines, and generally on hydraulic presses.) In the Charlottenburg Laboratory it is used on machines for testing stone. Hydraulic transmission and reduction of pressure is used by E m e r y in connection with a balance as described in Section 65b, Fig. 16.

b. Holding Test-pieces.

66. In order to hold test-pieces properly in the testing-machine they are usually provided with h e a d s or s h o u l d e rs, or they are placed in grips or jaws, without previous preparation, which hold them by friction between their surfaces.

It is customary to use pieces of c i r c u l a r or p r i s-m a t i c section for t e n s i o n-t e s t, usually r o u n d s or

flats; in crushing-tests it is customary to place the prismatic pieces having plane parallel end surfaces between flat plates of the holders of the machine.

A few of the typical holders shall be here described; the detail will be discussed later on.

Holders or Grips for Tension-test.

67. Round bars are either provided with shoulders or heads as shown in Figs. 23 and 24, or they are used as plain cylinders.

68. In case of use of heads, loads are transmitted from test-piece to jaws either by use of the bearing-surface under heads or by threads cut on the heads. In the first case, Fig. 23, the connection between test-piece and jaws consists of split rings or blocks *a*. In the second case, Fig. 24, a properly formed nut acts as the connecting detail.

69. Gripping a plain cylindrical rod by serrated wedges is shown in Fig. 25. These wedges slide in the jaws of the machine, their smooth backs bearing against the mutually inclined surfaces of the jaws, and thus jam their inner serreted surfaces against the test-pieces with pressure increasing with the loads applied. These inner surfaces are provided with teeth or file-marks very fine at the thin end and increasing toward the thick end of the wedges. When, however, because of faulty workmanship or defective action, the bearing in Fig. 23 is not true or normal, or when in Fig. 24 the axis of screw-threads is not coincident with that of test-piece, or when in Fig. 25 the wedges do not act so that the resultant of all forces passes through the axis of test-piece, then oblique stress will be produced in the latter.

These produce flexure of the bar, and the result of test may be materially affected. Therefore holding devices as shown in Figs. 23-25 should be used only when nicely finished test-pieces and properly constructed machines are used; otherwise provision must be made which excludes oblique stress as much as possible.

70. A device much used for this purpose is shown in Figs. 26–29, a s p h e r i c a l b e a r i n g. Originally test-pieces were provided with spherical bearings as in Fig. 26, but accurate results were extremely difficult to attain, and bars produced elsewhere rarely fitted the bearing-surfaces of jaws of the machine on which they were to be tested. Therefore forms similar to that shown in Fig. 27 have been generally adopted. The spherical bearing-block *b* made of hard steel fits the jaws of the machine and is recessed on the back to receive the split ring *a*, on which the shoulder of the test-piece takes a fair bearing. Bars with threaded heads, Fig. 24, are usually screwed directly into the nuts provided with spherical bearings, Fig. 28. Gripping-wedges are also similarly designed, as shown in Fig. 29.

In an opinion on making tests of resistance, published in the "Mittheilungen" (*L 114*), I made the following statements about spherical bearings: "A spherical bearing is to meet two requirements. Firstly, it is to equalize irregularities in finish of heads of test-pieces, and secondly, it is to provide for possible adjustment of the movable parts of holders, so that no bending moment can be brought to act upon test-piece. The second condition cannot in any case be met completely by a spherical bearing because of the friction between the bearing-surfaces, and it would therefore be in no sense impracticable to dispense with movable parts, and to secure the straining mechanism and the load-indicator in such manner that all lateral motion be prevented. The movable parts often produce more uncertainties than advantages."

"The contact between the sphere and its bearing must not be so constructed that the one or the other takes place on two separate, mutually movable bodies; the s p h e r i c a l p a r t and i t s s e a t m u s t e a c h b e c o m p o s e d o f a s i n g l e p i e c e. Both parts must be so formed that there is certainty of absolute sphericity and that they are ground or scraped together. The swivelling action must have no other action on the test-piece than that produced by the friction between bearing-surfaces; it must therefore be so constructed that in every possible case of mutual displacement of end surfaces the axis of the test-piece pass through the centre of sphere."

These conditions are fulfilled in the construction shown in Fig. 27.

"The closer the actual surface of contact of head of test-piece approaches the centre of sphere, the greater may be the displacement of the sphere in its bearing before the axis of test-piece passes beside the centre of sphere a certain (though minute) amount; and

the greater will be the possible adjustment due to inaccuracy of the head."

"In Fig. 30 a spherical bearing is shown in which the test-piece takes hold of the bearing far below the centre of sphere, and the spherical surface is difficult to finish accurately. But this design has the advantage of making the test-piece more accessible for measurements during test. To make the free length as great as possible *C* must be a minimum, or the head must be threaded as in Fig. 28 (which, however, is permissible only exceptionally, becausescrew-threads can only be made with sufficient accuracy when fitted to accurate gauges).

71. Bars of circular section can only be cut from pieces of ample dimensions. But in order to test the strength of plates or other thin sheets of material, it is customary to give them a quadrangular section, to use f l a t b a r s.

These flat strips are usually of uniform thickness, and the ends are wider and shouldered. The end is sometimes provided with a hole accurately drilled on the axis of the body of the strip, by means of which and the bolt *a* the bar is secured in the grips as shown by Fig. 31. It is also possible to grip the ends of the test-piece by serrated wedges, as in Fig. 32, without the previous milling of transverse grooves. When the latter are provided, the wedges are grooved with the same milling-cutter, to produce a perfect fit. In this case the wedges may be mere liners, as the test-piece will be firmly held by the grooves and ridges, without any lateral pressure. But wedge-shaped liners answer for gripping various thicknesses of test-pieces. Fig. 33 shows how this is attained in a somewhat different manner.

B a u s c h i n g e r strongly recommended the use of wedges with m i l l e d g r o o v e s, and serrated wedges have been frequently much objected to. I believe that my extended experience obliges me to express my opinion on this subject, by stating that each method when used at the proper time and occasion has its practical advantages. Liners with milled grooves can only act on the test-piece in a faultless manner, i.e., without producing bending-stress, when not only the grooves, but the liners as well, are made with absolute accuracy. This is, however, almost an impossibility, as will appear when considering their preparation. To mill these grooves the bar must be clamped four different times as a rule, adjusting it each time with great accuracy, without producing the slightest flexure by the clamps, if the grooves are to be directly opposite to each

other on the two sides, and also at right angles to the axis of the bar. It is of course possible, when working on a bar with parallel edges, to provide such chucks and stops in a milling-machine that a great degree of accuracy may be reached, as long as uniform standard pieces are used; but even then this becomes doubtful when the cutters are dulled and must be reground. Grooved lines, originally closely fitting, no longer fit; individual grooves take a bearing, others do not, and complete and correct bearing between ridges and grooves is only reached when the crushing limit of the ridge bearing first has been passed. This occurrence cannot, however, take place without producing initial bending-stress. What will therefore be the results when poor machines, and mechanics not carefully trained, are alone available? But even the perfectly prepared test-piece will only fit the liners before being placed in the jaws of the machine, because it is exceedingly difficult to prepare surfaces of the latter with such accuracy and maintain them in this condition that they fit accurately all at the same time. Liners with milled grooves should be fitted to the jaws in a manner similar to the spherical bearings, so as to be automatically adjustable, in which case the errors of adjustment in the jaws might perhaps be provided for, without, however, equalizing the effects due to inaccuracy of preparation of test-piece. One defect which has a most serious effect on precise measurements, the slipping of wedges, may be avoided, or at least minimized, by the use of liners with milled grooves.

The special objection to serrated wedges was raised that they injure the material by extreme lateral pressure and indentation, and that they very readily produce oblique stress, because they may act more effectively at one edge of the test-piece than at the other. This cannot be denied when wedges poorly made and carelessly applied are accepted. But by careful selection of proportions much may be achieved, and many objections are based on prejudice.

The objection to excessive lateral pressure is often valid under special conditions; but in the first place materials are sensitive to lateral pressure in a varying degree, and more so as their softness increases, as, e.g., Zinc (*L 115*), and in the second place this pressure may be reduced by increasing the bearing-surface between test-piece and wedges, or even distributed by proper design, that the pressure increases toward the end of the test-piece. In case of hard materials, such as hard steel and bronze wire, test-pieces also frequently rupture in the grips, and I shall refer to this later on. Injury to test-pieces by indentation may in fact be avoided by fitting the number, size, and depth of serrations to the material to be tested. He who wishes to test zinc would use wedges entirely smooth at the thin end and merely roughed by a file at the soft thick end.

Oblique action may of course occur when wedges are not so constructed that they can automatically adjust themselves to inequalities of test-pieces and to the jaws of the machine, just as is the case with the spherical bearing. This can, however, be attained to at least a very satisfactory degree, as shown below.

72. Spherical bearings are also used in case of flat bars to equalize those irregularities of shape as much as possible, which lead to oblique stress. Fig. 34 shows a type of this design. This, however, permits the use of only narrow strips, otherwise the dimensions become awkward.

In routine work it is not always possible to provide accurately finished test-pieces. Therefore many gripping-devices are in use which permit gripping-pieces provided with heads of trapezoidal section, as, e.g., pieces cut from flanges of beams and channels, which are to be tested without planed surfaces. As an example Fig. 35, showing the Mohr and Federhaff design, is given. In this the head of test-piece is provided with a hole which fits a bolt, also fitted to holes in both wedges. This prevents precession of either wedge or of the test-piece; at the same time the wedges may revolve about this bolt *d*, thus making adjustment to the sloping sides of the test-piece possible, while their backs take a proper bearing in the jaws.

There is, however, another method used with practical success in the Charlottenburg Laboratory since many years. In this type broad wedges with cross-serrations are used, which take hold of the central part of the ends of test-pieces, which latter have been slightly milled at their edges, as shown by Fig. 36.

In the device just described the proper function of the gripping-device, that of causing rupture of the test-piece at its centre, is retained by it. With earlier types of wedges, especially when the shape of the jaws had become slightly changed by frequent use, or when thin wedges, heavily strained by testing large sections, suffered small deformation, it happened that mirror apparatus, attached on two sides of the test-piece, showed very different extensions by the opposite mirrors; a sign that stress had been applied asymmetrically. Since using the new method the results have been materially improved. Care must, however, be had not to make the central gripping-surfaces too narrow and the heads short, because this will produce local overloading, the respective surfaces yield and influence (even previously thereto) the distribution of stress over the cross-section, thereby producing stress of the central fibres, as well as strain, which exceed those in the outer fibres. Practical require-

ments are that such dimensions be selected that the end surfaces plane before test shall in the worst case show only the slightest bulging after test (see Fig. 36).

Holders for Crushing-test.

73. The crushing-test cannot be made on comparatively long pieces, as in case of tension-tests; the sample must indeed be made very short, in order to avoid complicated action and to prevent lateral flexure or buckling.

As a rule, test-pieces for the crushing-test are made of circular or square section with parallel end surfaces, and of a length not to exceed twice the diameter or length of side. The test is made between two parallel, sufficiently hard plane surfaces of the machine, which take the place of the jaws. In order to insure perfect bearing against the pressure-surfaces one or both are habitually made adjustable, by giving them spherical bearings like Figs. 37 and 38. In order to adjust the pressure-surfaces parallel to each other and maintain them in this position, especially in horizontal machines, the pressure-plates are provided with three or four adjustable studs bearing against their backs, as in Fig. 38.

A defect found in many machines, especially those much used, is this, that the details themselves carrying the jaws permit greater or less lateral motion. This defect is of great importance in crushing-tests, because in them what may be termed unstable conditions exist, which produce the tendency to lateral motion, while the stresses in tension-tests tend to adjust themselves about the axis. Its disturbing effect is greater as the length of test-piece decreases. It is of primary importance that machines must be so designed that this is avoided, but a careful operator will always presuppose its existence and attempt to avoid or exclude it. Its effects become most disturbingly manifest in observations of elastic deformations.

For this reason I built the apparatus shown in Fig. 39 for the Charlottenburg Laboratory, in which carefully ground

pressure-plugs move in a cast-iron frame, thus avoiding any and all lateral motion of pressure-surfaces. But in order that the pressure of the machine be transmitted axially and also be measured with greatest possible accuracy, the pressure-plugs rest against spherical bearings. The tendency of the parts of the machine to lateral motion is reduced, because the distance between movable points (length of test-pieces plus length of both pressure-plugs to the centres of the spherical ends) is materially greater than the length of test-piece alone. This device, however, also possesses a defect, but which is probably without practical importance. In such bodies which are not homogeneous the (frictionless) rolling motion, under varying resistance, would tilt the pressure-surface. This is of course impossible in construction, Fig. 38; but a spherical bearing, as that in Fig. 37, may be fitted to the foot of the lower plug to permit of this action. It must, however, be remembered that friction of the bearing will also in this case act disturbingly. The device Fig. 39 has proven quite satisfactory in numerous and frequently very difficult investigations.

c. Measurements of Deformation and Measuring-apparatus.

74. At this time I shall give a short review of measurements and apparatus used for same in making tests of materials, and shall limit it to the necessities of the later sections.

Further reflections on methods of making these measurements will become necessary in the following paragraphs; the various designs of apparatus in particular, and their sources of errors, will be jointly discussed more fully later on.

A distinction is to be drawn between r o u g h and p r e c i s e m e a s u r e m e n t s for determination of dimensions and deformations of test-peces, in the latter of which we are concerned with determinations of changes of length of $\frac{1}{2500}$ in. (0.001 cm = mm 10^{-2}), or more frequently of $\frac{1}{10000}$ in.

in United States and English measure. Autographic records of stress-strain diagrams might be here considered as well; it is preferred, however, to treat of them more fully at the end of the book.

75. Rough measurements for determination of dimensions of test-pieces are made with familiar apparatus, such as scales, calipers and gauges, sliding and screw verniers, etc. Readings of the divisions are as a rule as fine as $\frac{1}{250}$ or $\frac{1}{2500}$ in. (0.01 or 0.001 cm), and tenths are estimated. In the United States and England $\frac{1}{1000}$ and $\frac{1}{10000}$ in. are usually the finest readings, with same estimation of whole divisions. The instruments themselves must of course be free from coarse errors, to be determined initially, and actual measurements must be made with careful elimination of defective manipulation.

Special apparatus must usually be employed for the determination of deformations during tests.

The principle of making measurements of deformation directly on the test-piece whenever possible should be generally observed, and not indirectly by relative displacement of parts of the machine (such as jaws, cross-heads, etc.). The latter is permissible only when practical considerations compel it, and when absolute knowledge about possible errors has been obtained. These errors may be caused by relative displacement of parts of the machine, by elastic deformation of such parts, and other causes; they must be determined by actual test or calculation if they are likely to produce important effects. When the test-piece is held by wedges, their slipping during loading may appear as errors in extension. When the test-piece is shouldered (Fig. 36), or otherwise departs from the prismatic form, its true length l_g, to which the measured extension relates, cannot be easily determined, and changes during test. The values found may therefore be seriously affected.

76. Direct rough measurements are usually made

by determining the variation of distance between two marks on the test-piece.

In Charlottenburg, scales divided in millimeters or in per cents of original length, l_g (gauge length), and with a groove on the bearing-edge, are used. Such wooden scales are attached by means of a wire clamp *a*, Fig. 40, in such a manner that the o (zero) coincides with a scribe-mark on the test-piece, while the other gauge-mark indicates the extension in mm or in % of length *l*. Care must be had that the zero and gauge marks remain in juxtaposition, which is easily attained by placing a very small bit of wax under the scale at this point. A similar, very practical device consists of a thin strip of sheet metal, shown in Fig. 41; it is held by a knife-edge-end fitting into a scribe-mark, and merely lies on the test-piece when horizontal, sometimes carrying a small weight at *a*. When used vertically, spring clamps hold it in position. As long as the length to be measured lies between 0.027 and 0.06 in. (0.07 and 0.15 cm) tenths, or $\frac{1}{10}$ per cents, may still be estimated with sufficient accuracy for very many purposes.

77. Test-pieces for crushing-tests are generally so short, and pressure-plates, in order that they may be appropriate for all possible cases arising, frequently are of such large dimensions, that direct measurement at the test-piece becomes impossible. Very many instruments for the purpose are therefore designed with this in view, and reliance is placed on measurement of relative motion of the pressure-plates, care being had that they do not deviate from their original parallelism, or provision must be made for measurement of possible displacements, or elimination of same.

Bauschinger (*L 116*) constructed a simple apparatus for this purpose. This apparatus, especially suitable for horizontal tests, is shown in principle in Fig. 42, which can be modified in many ways. A knife-edge, *a*, is placed on one head of the machine, or fastened thereto by a bit of wax; while a roller running on points is secured to the other. A wooden

bar rests on the knife-edge and roller, and is loaded if necessary. As the friction on the knife-edge *a* is greater than that of the pin-supported roller *r*, the latter will revolve when the heads approach each other, and the pointer, being rigidly secured to the roller axis, will indicate the angle of revolution of the roller on a greatly magnified scale on the divided circle *m*. The proportion of roller and indicator and the divisions on the circle may be so chosen that the apparatus can readily indicate $\frac{1}{250}$ in. (0.01 cm), and it is possible to estimate $\frac{1}{2500}$ in. (0.001 cm). The multiplication has been shown by experience to be quite reliable, and therefore the principle here shown has been largely used.

After students, who generally come to the laboratory in a condition of total unpreparedness, have attended a series of exhibition tests and measurements, I let them devote one or two days to the determination of errors of scales and measuring-apparatus. In this work the possible sources of error are briefly discussed, and the first opportunities for independent laboratory work are given.

78. Measurements of precision are primarily used in determination of elastic properties of bodies to be tested, and also for the location of the *Y*-point. In these cases not only the principle above laid down, that measurements must be made directly on the test-piece, holds good; but in addition the following: that they shall invariably be made on at least two opposite elements of the test-piece, must be especially observed. This is necessary in order to counteract or determine the effects of minutely oblique gripping, flexure of test-pieces, or non-homogeneity of material.

These causes produce unequal readings of the opposite instruments. At the same time the determination of averages eliminates errors in determination of changes of length when they are not too great.

The number of instruments of precision is very great; therefore only the principles underlying their construction can

be here discussed, and for this purpose micrometers and mirror apparatus shall be selected.

79. Elastic extensions of materials are almost invariably minute; and as test-pieces are generally made as small as possible in order to save material, cost of preparation, and cost of testing, instruments of precision for determination of small changes of length must possess the greatest possible accuracy.

The smallest factor of extension which is met with in testing materials is probably that of hard steel; it is hardly less than

$$e_f = 0.000\,000\,118 \text{ in. or } = 0.000\,000\,3 = 3.10^{-7} \text{ cm.}$$

When making tests within crements of load of 1422 lbs. per sq. in. (= 1kg/mm = 100 at.), which are suitable for practical work, there will be an extension of

$$e_1 = e_f s = 0.000\,000\,118 \times 10^2 = 0.000\,011\,8 \text{ in. } (= 3.10^{-7}.\,10^2 = 0.00003 \text{ cm})$$

for each 0.3937 of gauge length (0.01 m).

80. By using an accurate micrometer, having 5 threads per 0.03937 in. length (1 mm), the head of which is divided into 100 parts, values of

$$\frac{1}{50.100} 0.3937 \doteq 0.000\,007\,854 \quad \left(\frac{1}{50\,.\,100} = 2\,.\,10^{-4}\right)$$

can be readily read, and tenths of this value could be estimated; the estimated values would, however, have noticeable errors.*

If it be desirable to use such a micrometer for reasonably accurate measurements of extension due to $\Delta S = 100$ at. in case of hard steel, the total extension $\Delta e\%$ under stress of

* The facile use of the metric system will no doubt strike all readers.—G. C. Hg.

100 at. would have to be a sufficiently large multiple of the above factor of extension, in order that the errors of observation do not become too great. Assuming that 5 times the above factor suffices, $\Delta e\%$ under $\Delta S = 100$ at. should be

$$\Delta e\% = 5 \times 0.000\,007\,854 = 0.000\,039\,37 \text{ (or } 5.2.10^{-4} = 10^{-3}\text{ cm).}$$

In order to obtain this extension, the gauge-marks, between which these accurate measurements are to be made, the gauge length for precise measurement, should be

$$l_e = \frac{\Delta e\%}{e_1} = 13 \text{ in. (or } \frac{10^{-3}}{3.10^{-5}} \text{ or } \infty\ 33 \text{ cm).}$$

Micrometer-screws with such fine threads are, however, unpractical for use, their testing and calibration is very laborious, and the maintenance of the apparatus in perfect condition is exceedingly difficult. Therefore coarser threads are commonly used of .019685 or .03937 in. ($\frac{1}{2}$ or 1 mm) pitch; in the United States and England $\frac{1}{40}$ or $\frac{1}{50}$ in. pitch and 250 or 200 divisions of head. Hence either the gauge length l_e or the increments of load ΔS must be increased correspondingly. The apparatus is, however, always questionable, because the micrometer-heads make its attachment to the test-piece difficult (Fig. 43), which should be very positive, and because even then the unavoidable touch of the apparatus by hand while making measurements seems to endanger its adjustment.

Micrometers are in general use in the United States and England for measurements of elastic deformations. These instruments have probably been introduced there for the reason that heretofore less value has been placed upon measurements of precision than in Germany.

81. In 1873 Bauschinger introduced a method of measurement, in which he used the Gauss method of mirror readings; instruments constructed on this principle are called

"mirror apparatus" by the craft engaged in testing materials. Bauschinger's method has proved itself very practical, and is used in Germany in all official testing laboratories, and in many government shops, etc. In mirror apparatus, change of length is converted into rotary motion of the mirror, which is read off from scales mounted at suitable distances, by means of a telescope. These instruments are almost always attached to the test-piece in duplicate, thereby measuring changes of length on two opposite fibres of the material.

82. In Bauschinger's mirror apparatus, the same principle used in case of the roller apparatus (77) is employed, multiplication being produced by the rollers. A stirrup having two opposite knife edges is clamped to the test-piece, Fig. 44, and carrying two small pivoted rollers r, the prolonged axes of which carry the mirrors S. Springs f bearing against the rollers are held in position by a screw-clamp b, the knife-edges thus bear against the test-piece, while the other ends bear against the rollers r. Hence when the test length l_e elongates, the rollers are caused to revolve because of the friction between them and the springs. The springs therefore act on a constant lever-arm, namely the roller radius r, and the other lever-arm is replaced by a ray of light, without weight, which, because of the mirror effect, traverses twice the angle of rotation of the roller. Thus the length of this ideal lever-arm is equal to twice the distance A between the scale M, and the axis of the roller.

The velocity ratio and hence the multiplication of the extension e, indicated by this apparatus is the proportion $\frac{r}{2}. A$. This would be strictly accurate if the scale M were placed around the circumference of a cylinder whose centre coincides with that of the roller. But as the error, when the angular motion of the rollers is small, and in fact for our purposes, which chiefly relate to comparisons may practically be con-

sidered negligible, it is preferred for reasons of convenience to use the straight scale. This may then be mounted at any desirable distance from the roller axis. Thus the magnification of e is completely under control.

83. The ratio of the ideal lever system is

$$n = \frac{r}{2A},$$

and as two mirrors are invariably used simultaneously, half the sum of the readings $a + a_1$:

$$\frac{a + a_1}{2} n = e = (a + a_1)\frac{r}{4A}.$$

The scale is divided in millimeters (or in % of length l_0). If the reading $(a + a_1) = 1$ mm, i.e. 0.1 cm, is to show the extension of the test-piece $e = 0.0001$ cm, or in the sense as explained under Section 80, the value for one unit division of length $= 10^{-4}$ cm, in case of a radius of roller $r = 0.3$ cm:

$$m = (a + a_1)\frac{r}{4A} \quad \text{or} \quad 10^{-4} = \frac{10^{-1}.3 . 10^{-1}}{4A},$$

or the distance of the scale for mirror axis

$$A = \frac{3 . 10^{-2}}{4 . 10^{-4}} = 75 \text{ cm}.$$

The only mirror apparatus built to U. S. and British standards is the "Henning," in which the scales are divided into hundredths of inches, the scales are distant 5 ft., and the diameter of roller (knife-edges) is 0.24 in.; hence $A = \dfrac{.24}{4 \times \frac{1}{1000}} = 60$ in. $= 5$ ft.

—G. C. Hg.

84. When the graduation of the scale is such that the field covered by the width of the cross-hairs in the telescope is relatively only a small part of it, then even tenths may be estimated with great accuracy. In this case values could be estimated to the $\frac{1}{100000}$. These values obtained from actual

use show that not only the estimated values are quite accurate, but also that the transfer of motion of the rollers by the friction between the latter and the springs f, Fig. 44, is very positive.

85. When using the increments of load of $\Delta s = 1422$ lbs. (= 100 at.) as in the case of micrometers, and assuming a strain of 5 times the factor of extension, then

$$l_e = \frac{5m}{e_1} = \frac{\Delta e\%}{e_1} = 6.69 \text{ in.}\left(= \frac{5 \cdot 10^{-4}}{3 \cdot 10^{-6}} \text{ or } \infty\ 17 \text{ cm}\right).$$

Because of the great accuracy of readings, the gauge-length may be taken still smaller.

86. When taken strictly, the equation $n = \frac{r}{2A}$, as has been already stated, does not accurately represent the ratio of the apparatus. It is necessary to obtain a knowledge of the errors committed.

In Fig. 45 let α be the angular motion, A the distance of scale; then the true reading would be the length of arc a', while actually a length a was read off on the tangent. But $a = A$ tang 2α, or tang . $2a$ for $A = 1$. The length of arc for radius 1 and one degree of arc is

$$\Delta a' = \frac{2.1\pi}{360} = 0.017\,453.$$

Calculating the values of a for various angular motions α of rollers = tang 2α and a', and stating the differences between the values of the two in % of a', we will then have the errors by which a has been found greater than a', as follows:

Table 5. **Errors of Mirror Apparatus when reading off on Flat Scale.**

α	1	2	3	4	5	10	15
a	0.03492	0.06993	0.10510	0.14054	0.17633	0.36397	0.57735
a'	0.03491	0.06981	0.10472	0.13962	0.17453	0.34906	0.52359
$\frac{a - a'}{a'}100$	0.03	0.17	0.36	0.66	1.03	4.27	10.27%

If it is desired to picture to oneself all possible errors when making a tension-test, the following conditions should be noted:

If the P-limit in case of the steel test-piece is found at 42,660 lbs. (3000 at.), and $l_e = 5.9$ in. (15 cm), then for $a = 0.000\,000\,3$

$$\epsilon = a \cdot sl_e = 0.000\,000\,3 \times 42{,}660 \times 5.9 = 0.068\,356\,2.$$

If besides the radius of roller is $r = 0.11811$ and circumference of roller $= 2 \cdot \pi \cdot 0.11811 = .710692$, then the angle of motion of the mirror for $\epsilon = 0.005315 =$

$$\measuredangle\ \alpha = \frac{0.005315}{0.710692} \cdot 360 = 2.58^\circ.$$

Hence the error when using the flat instead of curved scale is according to Table 5 less than 0.4%. If it should at times become necessary to attain greater accuracy, it is easy to make the corrections by calculation or by comparison with table of corrections for Gauss' Readings, which are published in many places. Fig. 45 will show at a glance that this error may be reduced by one half if care be taken that the initial and final readings be equally distant from the normal to the scale passing through the axis of mirror. Moreover when the above method is to be avoided, it is easy to decrease the value of A slightly, so that the error inherent in some of the readings may become negative.

87. Bauschinger's apparatus is so designed in detail that it is somewhat heavy; having been constructed with the special purpose of use on the Werder machine, it is rather difficult to use it in a vertical position. It was therefore desirable for the Charlottenburg Laboratory, in which much work was done on vertical machines, to have an apparatus which was handy and applicable for a variety of purposes. This was my incentive for designing a number of mirror apparatus which were built by the laboratory mechanic.

88. In the Martens Mirror Apparatus the roller is replaced by a piece of steel of rhombic section which carries the mirrors. This body, r, Fig. 46, rests with one edge, o, in a groove in the spring f, while the other bears against the test-piece, being held against it by means of spring clamps b straddling the springs f. The other knife-edge ends of these springs bear against the test-piece. Thus the rollers of the

Bauschinger apparatus are done away with. During extension of the test-piece the mirrors revolve, which is determined by reading a scale M by the telescope F. The distance across the opposite knife-edges carrying the mirrors is the measure of r. The plane of the mirrors lies in the axis of revolution o, Fig. 47.

When the mirror revolves around o through an angle α, the beam of light travels over 2α. Hence

$$e = r \sin \alpha \text{ and } a = A \text{ tang } 2\alpha, \text{ or}$$

the ratio $$n = \frac{e}{a} = \frac{r \sin \alpha}{A \text{ tang } 2\alpha}.$$

But as only small angles α are traversed we may say that n is approximately

$$n = \frac{e}{a} = \frac{r}{A}\frac{1}{2}.$$

And as two mirrors are used simultaneously, it follows that, expressed by the sum of both readings a and a_1,

$$e = \frac{a + a_1}{2} n = (a + a_1)\frac{r}{4A},$$

as was the case in the Bauschinger apparatus.

89. Calculating a table of errors as was done in case of the Bauschinger apparatus, and in order to obtain a knowledge of their magnitude from the equation $n = r/2A$ for the same angles α, we shall obtain the following:

Table 6. **Errors in Martens' Mirror Apparatus.**

Ratio. a	1	2	3	4	5	10	15
Approximate $n = \frac{1}{2}\left(\frac{r}{A}\right)$	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Correct $n' = \frac{\sin a}{\tan 2a}\left(\frac{r}{A}\right)$	0.49977	0.49909	0.49798	0.49637	0.49431	0.47710	0.44829
Error of Reading $= \frac{n' - n}{n} \cdot 100$	0.05	0.18	0.41	0.73	1.15	4.80	11.54%

The values given in the last line show the amounts by which the true values are less than those obtained by the approximate determination.

By comparing these results with those in Table 5 it will be seen that the apparatus is theoretically less accurate than that of Bauschinger when using equal values for r. But practical advantages are obtainable because of its design, and by choice of proper values for r and slight change of A (as stated in Section 86), so that it can be made equally accurate with the Bauschinger apparatus, although it contains other theoretical sources of error.

a. It is not always easy to place the knife-edges in the same initial position on the test-piece, and the effect of the difference of angle β with the normal to the scale must be determined.

According to Fig. 48,

$$\lambda = r[\sin(\alpha + \beta) - \sin\beta], \text{ in Case I, or}$$
$$\lambda = r[\sin(\alpha - \beta) + \sin\beta], \text{ in Case II.}$$

Hence, as $a = \text{A tang } 2\alpha$,

$$n = \frac{\lambda}{a} = r\frac{\sin(a \pm \beta) \mp \sin\beta}{\text{A tang } 2\alpha}.$$

Table 7 is calculated precisely as Nos. 5 and 6.

Table 7. Errors in Martens' Mirror Apparatus due to Improper Initial Adjustment.

α = angle of rotation; β = angle of initial adjustment.

	α	1	2	3	4	5	10	15
Case I, Fig. 48:	$\beta = 3$	0.23	0.41	0.70	1.07	1.54	5.43	12,47
$n' = \frac{\sin(\alpha+\beta) - \sin\beta}{\text{tang } 2\alpha}\left(\frac{r}{A}\right)$	$\beta = 2$	0 12	0.30	0.56	0.92	1.37	5.19	12.11
	$\beta = 1$	0.06	0.21	0.46	0.80	1.25	4.98	11.81
	$\beta = 0$	0.05	0.18	0.41	0.73	1 15	4.80	11.54
Case II, Fig. 48:	$\beta = 1$	0.06	0.18	0.39	0.69	1.09	4.66	11.30
$n' = \frac{\sin(\alpha-\beta) + \sin\beta}{\text{tang } 2\alpha}\left(\frac{r}{A}\right)$	$\beta = 2$	0.06	10.18	0.39	0.68	1.06	4.55	11.09
	$\beta = 3$	0.12	0.21	0.41	0.69	1.06	4.46	10 89

Table 7 shows that adjustment as in Case II is more favorable. For this reason it is advisable to make the distance between knife-edge and groove on springs f a little greater than l_e (Fig. 46) on the test-piece.

b. Taking the dimensions of the apparatus used at the Charlottenburg Laboratory as an example, and calculating the angle α as was done in case of the Bauschinger apparatus, obtained as under conditions stated in Section 86, we shall find when $S_P =$ 42,660, $l_e = 5.9$, $a = 0.0000003$; and again when $e = 0.005315$, and a width over knife-edges $= 0.157 +$,

$$\sin \alpha = \frac{e}{r} = \frac{0.005315}{0.157 +}, \text{ or } \measuredangle\ \alpha = 1.56^\circ$$

The error committed by reading on a flat scale and by using the approximate value of $n = 0.5$ will not exceed ($\beta = 3^\circ$) 0.4%, as shown by Table 7, even when assuming a very inaccurate initial adjustment; hence the work is done under conditions equally as favorable as when using Bauschinger's apparatus, which is attained by the possible use of a larger value of r.

I shall not refer to the manifold applicability of the fundamental principle used by myself, but shall at this time content myself with referring to this subject later on in this work, merely calling particular attention to the fact that I there describe means and ways to materially reduce the errors above discussed.

90. In addition to the singular errors of theory, there are those due to the construction and to the method of observation common to both types of mirror apparatus, as well as those due to external condition, which must be considered. However, it cannot be the object of this handbook to discuss this entire series of sources of errors exhaustively, although it is perhaps desirable to consider the most important, because the work of many an observer will be facilitated, and casual annoyance avoided, by calling his attention to points easily forgotten at first, or which may be over estimated. It is in fact the highest art of the observer to avoid sources of error as much as possible, and to minimize their effect.

91. The accuracy with which mirror apparatus works is primarily dependent upon the accuracy with which the two chief factors r and A have been determined, and that the scale is correct.

The length A can easily be measured to $\frac{1}{50}$ in. (0.05 cm). In this case the accuracy is $\pm \frac{1}{50}/A$, or when, as in actual conditions, A is taken as 5 ft. (or 100 cm in Europe), the accuracy of measurement of $a = \frac{1}{50}/60 = \frac{1}{3000}$ (or 0.05/100

$= \frac{1}{12500}$ German). If it is desirable to have the same accuracy for values of r, then r must be measured to an accuracy of $\frac{r}{3000}$, or when $r = 0.24$, then $\frac{.24}{3000} = 0.00008$ in. (or German $\frac{0.4}{2000} = \frac{1}{5000}\Big)$.

92. Special instruments of precision are of course necessary for this purpose, whose errors have been accurately determined, and which are maintained under constant supervision. Instruments of this kind are described further on; they are very expensive, and but few public institutions are provided with them. Those who do not possess them act wisely by having the rollers or knife-edges of their mirror apparatus compared from time to time, because both change their dimensions by use. In the case of the Bauschinger apparatus the change of diameter of rollers is rarely visible externally, while changes of knife-edges are generally visible; the edges, originally sharp, take a polish.

93. The rollers of the Bauschinger apparatus must also be examined for uniformity of diameter, and whether the surface is concentric with the axis of rotation. In the Martens type it must be ascertained whether the two knife-edges lie in a plane, and are also strictly parallel to each other.

94. The plane of the reflecting surface should pass in both types, as nearly as possible, through the axis of rotation, for if it be eccentric the readings will be either too large or too small, as shown by Fig. 49 at a_2 and a_1. In Fig. 49 the eccentricity of the reflecting surface s is assumed as equal to m to an exaggerated degree, and that in one case this plane passes through axis of rotation o, in the others through points 2 and 1 further from or nearer to the scale. Distances A are usually measured by a standard bar after the apparatus has been attached to the test-piece. One end of this standard is butted against the scale, while the other, provided with a thin strip of cardboard, is used as a feeler,

which will just touch the mirror upon shifting the scale into its proper position. Hence the distances A_0, A_1 and A_2 may be assumed as equal, for our purposes, in every case. If the amount of displacement of the mirror be uniformly α, then the rays indicated by the full lines tipped by arrows will be reflected into the telescope F by the mirror at 0, 1 and 2; hence a_0, a_1 and a_2 will be the divisions of scale read by the telescope, of which a_0 alone would be correct. If the revolutions of the mirrors s_1 and s_2 had occurred about points 1 and 2 as centres, and been equal to α, the readings would have been as shown by the broken lines, and equal to a_0 in all three cases. Because of the eccentricity, however, the actual readings would have been a_1 and a_2, which are affected by the error Δ_a; a_1 is too small and a_2 too large. It is readily seen that initial adjustment of mirrors provides ready means for partly avoiding the errors due to approximate calculation or observation, discussed in Sections 86 and 89, when using a flat scale. This would, however, be of slight practical value, as will be presently shown.

1. The Bauschinger, Martens, Kirsch, and Henning mirrors are so designed that they permit slight rotation of the mirrors about an axis parallel to that of the test-piece (normal to the axis of rotation of mirrors), so that they may be adjusted to reflect the longitudinal axis of the scales. When it is occasionally necessary to set the *mirrors to a larger angle with the axis of rotation, the errors thereby introduced must not be neglected* when making accurate investigations. This inclination becomes necessary when the telescope and scales are so mounted that the line of sight makes a large angle with the normal to the axis of revolution and at the centre of mirror. The reflected rays do not then continue to travel in a plane, but travel in a curved surface, the intersection of which, by the reflected image of the scale, becomes a parabola, instead of a right line. It must be observed that the error arising will be further magnified by the attempt to measure the distance A between the scales and

mirrors, when their adjustment causes a considerable deviation from the normal plane. A must rather be invariably measured on the normal from the axis of revolution of the mirror to the scale. In this case there will be no very serious error, even if there be considerable deviation from the normal plane.

2. Many designers have attempted to construct mirror apparatus which, although attached to two opposite fibres, have but a single mirror, so that but a single telescope becomes necessary. The matter appears very enticing, because labor of observation is diminished; but there are two points of view. The use of two mirrors with reverse directions of motion has the great practical advantage that distortions of test-piece and of the mirrors attached thereto, in the normal plane of the mirrors, can have no effect on results as long as A is not changed thereby. Distortions of test-piece and mirror apparatus in any other plane make themselves immediately manifest, as lateral displacement of the scale with reference to the cross-hairs. Distortions in the normal plane manifest themselves by the equal simultaneous increase and decrease of readings in the two mirror-readings; hence they cannot disturb results when two mirrors are used.

The use of one mirror causes the loss of this advantage, and also the immediate possibility of recognizing the errors committed.

Displacement or shifting of test-pieces in space will, however, not be entirely prevented in most machines. Machines with heads laterally fixed have the advantage in this respect; but even these must not be depended upon implicitly when making accurate measurements.

95. As in measurements of precision small changes of length of bodies of relatively great length are concerned, thermic changes of length of test-piece or of the mirror apparatus cannot be neglected in those cases where great

accuracy is desired. Taking as an example the steel bar previously referred to, whose coefficient of thermal expansion for 1° C is $\beta = 0.0000124$, the apparent elongation of $l_e = 5.9$ for each C° of thermal change, between test-piece and attaching spring:

$$\Delta l_e = 0.0000124 \cdot 59 = 0.000073 \text{ in. } (= 0.000186 \text{ cm}).$$

If the magnification of mirror apparatus be $n = 1/1000$ the sum of readings of scales for Δl_e would be $0.000073 \times 1000 = 0.073$ in. ($= 0.186$ cm). But hundredths of centimeters $= \frac{1}{250}$ in. can be readily estimated; hence it will be readily understood that a change of temperature between test-piece and apparatus of only $\frac{1}{20}$ C° may begin to affect the measurements.

For this reason an interval of 10 minutes must elapse, when doing very accurate work, between the adjustment of the mirror apparatus at 0 load and the beginning of test, during which period the mirrors must show no further variations, i.e., when the thermal differences produced by manipulation during adjustment of the parts have entirely disappeared.

96. It is of course possible to vary the effect of thermal changes of the springs by selection of materials which have a small coefficient of expansion, or such which are poor conductors. Thus I used, for example, hollow square wooden tubes in the mirror apparatus described further on in connection with the 500t. machine, while Prof. H. T. Bovey substituted a wooden spring in his Unwin mirror apparatus, saturated with paraffine to protect it against moisture. Bovey claims to have reduced the thermal effects to $\frac{1}{18}$ of that found to occur when previously using a steel spring. At the same time it must not be forgotten that the error due to thermal change is not caused by the springs alone, but also by the change of the test-piece under the same influence. What affects the accuracy of measurements

is always only a change of relation between test-piece and springs produced by thermal action and conditions.

In my course of lectures I describe the sources of errors of micrometers and mirror apparatus with sufficient detail, without, however, being exhaustive, that the students may become imbued with the fact, in the very beginning, that all of our methods of observations and instruments have inherent errors, and that in all cases where numbers are obtained by practical observations they are always subject to errors.

Calculation based on theoretical principles can always be made with absolute accuraracy; the results of such calculation may be correct when the principles are correct. But it cannot be expected that figures obtained by routine observations coincide accurately with those obtained theoretically, even when the theory is correct or the observations were made in a manner entirely free from objections. The art of the observer consists in every case of making the test in so perfect a manner that all methodic errors are avoided, and that the result, if possible, be affected by unavoidable accidental errors alone.

These may be determined by methods of elimination (*L 103, 104*, etc.), although unnecessary in most cases, and thus secure an opinion of the accuracy of observations.

The observer should always obtain a correct opinion of the possible and of the probable errors inherent in the results obtained by himself. He who clearly recognizes the errors which may exist in results obtained by him or by others, or which may be found in them, will never commit the nonsense so often perpetrated, of adding to reliable values meaningless figures obtained by calculation or even decimals, or even actually using them in calculations. Such procedure most readily indicates the quality of mind possessed by the originator.

97. Fortunately the subject is by no means as difficult in the field of testing materials as the foregoing description of sources of error might lead one to believe. The materials are in themselves so variable that there would be no utility in examining each by the finest physical methods, or of making all corrections and eliminations. Moreover our testing-machines cannot show too great superiority in regard to their indications of loads applied, as a thorough investigation will readily reveal. When stresses S_P, S_Y, S_M have been determined within 10 at. with certainty,

we may be well satisfied, for even this degree of accuracy is rarely attained. In this work the results shall always, as is generally customary, be stated to the nearest 150 lbs. (10 at.), unless they be averages obtained from an extended series of tests.

98. The use of instruments of precision in tests of materials is rarely intended for the purposes of determining absolute lengths; in such exceptional cases all sources of errors mentioned must of course be fully allowed for. Mirror apparatus serves in most cases, as does the galvanoscope in the hands of the electrician, rather as a very delicate indicator for the instants of passing beyond the proportional, P, and yield, Y, points. These determinations might in fact be made ultimately, as appears from the definitions of P and Y points in (*37*) and (*38*), without absolute measurements of extension, e; in fact it could be found even when the ratio of multiplication of the mirror apparatus was entirely unknown.

The determination of the factor of elongation e_f and of the Modulus of Elasticity E do, however, require absolute measurements to be strictly correct; but in actual tests of materials this figure is of subordinate value, and the degree of accuracy usually found in instruments is generally amply sufficient.

An accurate knowledge of E, modulus of elasticity, becomes of the first importance in the construction of suspension bridges, as the cables being suspended freely, loaded only by their own weight, are later on subjected to very greatly differing elastic deformations during erection of the structure and after completion thereof. My personal experience on the New York and Brooklyn, the Youghiogheny, the 7th St. Pittsburgh, and the Covington and Cincinnati bridges, has shown the absolute necessity of a correct knowledge of E, to avoid grave practical complications.—G. C. Hg.

3. Effect of Heads or Shoulders.

99. When making an actual test, the assumption made in (*33*) that the test-piece have a very great

length in proportion to its cross-section can no longer be adhered to. The test-pieces must rather be not only relatively short, in case of crushing-tests even very short, but they must furthermore be provided with gripping heads or shoulders for tension-tests (*68*), which are replaced in the crushing-test by the flat end surfaces (*73*) by which the loads L are transmitted to the material. These methods of holding always produce an effect on the results of tests, and it therefore becomes necessary to form an opinion of the conditions produced thereby.

Tension Test.

100. If the test-piece were long and the pulling-head (Fig. 50) wanting, the cross-section would diminish under effect of load L (i.e., diameter of round bar shown); d would change to d'' (*35*). But when a head is provided the material immediately adjoining it is not free to yield (*L 105, 118* and *119*); resisting forces S are developed, which make possible only very small, practically unnoticeable, decrease of cross-section of the head. In the adjoining section of the bar ef the effect of the head is less noticeable. The decrease of cross-section will therefore be more decided, and points e and f will move to e' and f'. During this change the volume of sections $a\,b\,e\,f$ and $a\,b\,e'\,f'$ will remain constant under the assumption that the material have a density $= 1$. Forces S' resisting the diminution of cross-section at $e'\,f'$ are smaller than S. See Barba (*L 118*, p. 686; *119*, p. 1–75).

If the bar be of sufficient length, the forces S at a great distance from the head will become disappearingly small, and the cross-section will assume such dimensions as it would have if the bar were not provided with a head. Without the influence of the heads, points a and b would have moved to a'' and b'', points e and f to e'' and f'', volume $a''b''e''f''$ remaining $= abef$.

The shape actually assumed by a shouldered round bar

under load L is hence not truly cylindrical; the bar rather assuming the shape of a body of revolution, whose generatrix passes through a, tangent at its centre to the ideal cylinder $a''b''e''f''$ of diameter d'', provided the length of bar permits it, i.e., if it be sufficiently large.

101. The load L, which acts on all sections of the bar simultaneously, under the conditions assumed, must produce different conditions of stress in individual sections, because of their different areas. Although this is not strictly accurate, be it assumed that the load L is uniformly distributed over every section. A conception of the relative degree of stress in the individual sections may thus be formed without specific calculation.

Constructing a diagram based on previous assumptions to a base line A, Fig. 51, with areas of sections and extensions e_1 as co-ordinates, we shall obtain the $e\%_1$, $e\%_2$, $e\%_3$, line $f_1 f_2 f_3$, representing f, and $e\%_1$ $e\%_2$ $e\%_3$ as of e_1. Because of assumption that $V = e_1 a =$ const., $e\%_1 = e\%_3$ must be infinitely small, because the section of bar under the head decreases but minutely; besides $e\%_2$ for the central unit section must be a maximum, because f_2 is a minimum. Dividing the load L by the area of cross-section, we shall obtain the stress S; and these can also be plotted as a diagram with line CD as a base. In this $\sigma_2 > (\sigma_1 = \sigma_3)$ or $S_2 > (S_1 = S_3)$.

101a. Stresses ρ resulting from effect of head are greatest in sections 1 and 3 and small in 2, or infinitely small when the bar is very long. The stress ρ is, however, evidently $= 0$ in the axis of bar at all sections; hence stress ρ must decrease from the surface to the axis of the bar at all sections, as represented by the diagrams with lines 1 and 4 as axes for sections 1 and 4.

Considering next a diagram of a meridional section of the bar on which have been plotted all of those points which were originally equidistant from the axis (fibres), we already know the shape assumed by the external and internal fibres during

deformation. The stress of each fibre in its direction can again be shown on a diagram for each section of bar, by plotting stresses S and forces ρ with GH, Fig. 52, as a base, and resolving them for every point of the radius of section in the direction of fibres.

We thus obtain diagram $Gbb'M'$, in which aa' is the direction of extreme fibre, and bb' that of the middle fibre MM'; α is the angle of inclination between the direction of fibre and the axis of test-piece MM'; it is greatest for the extreme fibre. The construction of the two diagrams for S_a and ρ_a will be readily understood from Fig. 52.

The diagrams give no information about the actual magnitudes of S and ρ (S_a and ρ_a); and the question where the maximum stress is to be found in any given section cannot be decided. The axial stress $= S$ is identical in every section, and relatively a maximum in the axis of test-piece. The stress of extreme fibre depends upon the relation between between ρ and S and the angle α. As α is always equal to 0 at the axis (section f_2), the stress in every fibre at that point, even the extreme fibre $= S$, and this is a maximum because the sectional area is a minimum. Neither can it be asserted with certainty whether the stress in the extreme fibre also decreases toward the ends, as in the middle one; it may, however, be assumed, because it is a fact, that contraction (and rupture) always occurs at the centre of perfect test-pieces (*L 119*, p. 1–75).

102. The above considerations permit the following important practical conclusion: *However the holding-devices or ends of test-piece may have been constructed, the principal object of both is to prevent contraction taking place at the section where the test-piece merges into that part of it where it is gripped.*

103. As, because $v =$ const., the contraction and changes of length progress hand in hand, *even those gripping-devices which prevent elongation of the bar*

within the part gripped answer the purpose. For this reason it is easy to grip test-pieces without heads, as between serrated wedges, in such manner that rupture occurs in the free part between them. This method of gripping may, however, affect the results of tests for other reasons (*71*), and hence it is generally used for routine tests only. In Section 71 it has been stated that this is frequently based on prejudice. The Emery holding method (described at end of book) is a proof that the above-described principle of elimination of extension may be utilized with advantage.

a. The effect of holders should, however, be proved within the proportional limit when using very delicate instruments of precision, and by use of short gauge-lengths l_i, applied first close to the head and again at the centre of the bar. I have tried this on low-steel bars, but without striking success. The secondary stresses or non-homogeneity of material must have obliterated the effect of the holders, for I found in many cases up to 1 % less extension near the head, while occasionally even greater values than at the middle of test-bar.

Bauschinger plainly demonstrated the effect of bearing-plates on elastic deformation in his investigation of stone (crushing-tests).

b. The previous considerations, however, lead to still further conclusions, which shall now be briefly stated. As a result of the effects due to heads, the contraction and extension of cylindrical bars could be decreased, and at the same time increasing the resistance by simply providing the bar with collars or ridges at short intervals. Such a bar should always break in that groove which is the widest. The effect of threads of a screw (produced by cutting-tools) is similar; the threads or collars cut at regular intervals of equal section, Figs. 53–55, take the place of heads of test-pieces, and hence screws are always stronger than a bar having a section equal to that at the root of the threads, made of the same material. The body of the screw (of low steel), however, suffers a considerable extension. Preventing this extension by providing fitting nuts on the threads at various points, a successive increase of the resistance of the screw is produced* (even though this can hardly be established by test). At the same time it may be stated that fracture must take place within the greatest free length between two nuts. It is, however, a fact that bolts under tensile stress alone rarely ever break off within the nuts in actual service.

* Because of the shortening of the free length of bar between the heads (nuts) the forces ρ (50) in the centre of the part of bar limited by the nuts will be increased beyond those in the long bar; hence a will be greater and S_M must also become greater thereby.

c. Why are some materials so insensitive during tension-test to slight injury to section? Why are especially hard and brittle materials so sensitive to gripping-wedges? Why do hard materials break more frequently away from the middle of length of bar, and oftener close to or within the holders, than soft materials? A part of the causes is "effect of the heads."

The slight diminution of cross-section need not necessarily be the cause of diminution of resistance. Proof of this fact may be had daily in making tension-tests. In many laboratories test-pieces are provided with numerous cross-marks (divisions [*137* and *156*]); it is in fact customary to score the gauge-marks for mirror apparatus entirely around the test-bars. Nevertheless rupture occurs so rarely in these marks that official laboratories, which undoubtedly never fail to exercise all care, do not hesitate to use them.

Frequent rupture of hard and brittle materials in the grips is, besides other causes, produced by the impossibility of proper action of heads or of gripping-devices, as previously explained, taking place. Because the extensibility of such material is very small, its contraction of section is very small. The effect of the heads hence cannot become pronounced, any more than the prevention of change of length within the grips or holders can become effective. For these reasons especially the gripping of material of slight extensibility is very difficult (hard-drawn wire, cast iron, etc.); moreover they do not stand the secondary bending-stresses, which are hardly avoidable any more than the most insignificant superficial injuries, because in their case every injury acts as a reduction of cross-section.

Soft materials are especially susceptible to lateral pressure. When the gripping-wedges exert such intense lateral pressure that yielding takes place within the holders, during simultaneous application of tension-stress, they cannot fulfil their office—prevention of lateral or longitudinal extension (*103*). Zinc, leather, paper, etc., are sensitive to lateral pressure, hence the surfaces of holders must be made large.

d. The above facts are partly verified by Table 8.

The tests were made to determine the effect of shape of thread on the strength of bolts. For this purpose, bolts with threads as shown in Figs. 56–59 were cut in a lathe on bars, so that the diameters at root of threads, as well as in grooves, were respectively about 1 in. (2.4 cm) and $\frac{1}{2}$ in. (1.3 cm).

The results of tests were then compared with those obtained from cylindrical test-pieces of the same diameter and material. The fractures and deformation are shown by Figs. 53–55.

The proportional strengths given show at a glance that the increase of tensile strength due to the grooves may be estimated at from 9–17%, and that due to threads at from 10–19%.

Table 8. Tension-tests of Threaded Bolts and of Ringed Bars.

Material: low steel (Flusseisen). The figures are averages of two tests. (Martens, Influence of Form of Threads on the Strength of Screw-bolts, Ztschr. d. V. d. Ing. 1895, p. 505.)

No.	Type of Threads or Collars. Figs. 56–39.	Shape of Thread. (l = length of prismatic part of rod.)	Diam. at Root of Thread 1 in. (2.4 cm).				Diam. at Root of Thread ½ in. (1.3 cm).			
			Maximum Stress S_M.		Proportional Strength.		Maximum Stress S_M.		Proportional Length.	
			Rings a in at.	Threads b in at.	Rod 5 = 100. a	Rod 5 = 100. b	Rings a in at.	Threads b in at.	Rod 5 = 100. a_1	Rod 5 = 100. b_1
1	Sharpthread $\angle = 55°$	$l' = 0$	4390	4330	116.8	115.2	5000	4960	114.9	114.0
2	Whitworth.........	$l_2 \sim 0$	4370	4310	116.2	114.4	4760	4880	109.4	112.2
3	German Engineers' Standard.	l_3 } small	4270	4300	113.6	114.4	4870	5180	112.0	119.1
4	U. S. Standard.....	l_4 } small	4240	4220	112.2	112.8	4940	4790	113.6	110.1
5	Standard round....	l_5 very long	3760		100		4350		100	

104. In practice efforts are made to minimize the effect of shoulders. For this purpose long tapering necks are turned under the shoulders, as shown in Fig. 60, for the round bar. Moreover the measurements of length are not made on the entire parallel part, l, between tapers, but on only a part of it, called the gauge-length, l_r.

a. On the basis of the considerations appended to Section 103, the question may be asked whether it is at all proper to provide a tapering part between the body of bar and the shoulders?

This question can in fact be answered only conditionally. When testing materials having slight extensibility the tapered neck will be advantageous, because injurious effects due to secondary bending-stresses, produced by defective gripping, will be counteracted to a certain extent. In case of ductile materials the tapering neck will be useless, because the stress S and elastic extension e will decrease in proportion to the increase of cross-section, and a similar occurrence would take place as in the case of shoulders.

To determine this I had a series of tests *A* made of bars with very gradually tapering necks, about as in Fig. 60, and a series *B* with square shoulders, without fillet or taper. The bars were of the same diam. = .80 in. (2 cm), and taken side by side from a piece of very uniform material. They were provided with cm divisions, whose lengths were measured both before and after test. The means of elongation $e\%$ of the divisions on the bars are plotted in Fig. 61, in which these elongations are plotted as ordinates to the numbers of divisions.

It will be seen that the elongations in both cases are considerably less in the end divisions, and that the elongations of middle divisions increase materially, precisely as assumed in Section 101. A comparison of lines *A* and *B* shows that although the effect of a square shoulder is but slightly shown ($e\%$ is about 2% less than in *A*), the difference already disappears in the second centimeter division.

b. The effect of shoulders on the extensibility of ductile material (low steel of $S_M = 57,000$ lbs. per sq. in. = 4000 at.) would have been more thoroughly prevented if the cylindrical part of the test-piece had been made longer by the length of the tapering necks (which was 3.5 diameters at the end). The success obtainable can be estimated from Fig. 61 when it is remembered that the divisions of the bar of 2 cm diam. were 1 cm long. Seven divisions would have been added at each end of the body of bar, and as the effect of shoulders is shown in Fig. 61 to be already very slight at divisions 2–4 (the lines being always parallel to the base line), the continuation of the cylindrical body as such, instead of with tapering necks, in spite of equal length, would certainly have been advantageous.

It is hardly necessary to repeat that the effect of shoulders is variably noticeable in different materials.

Crushing-test.

105. As has been seen, shoulders and heads, or the gripping-devices replacing them, have an effect upon the distribution of stress in and the deformation of a test-piece subject to tension, and this suggests the inquiry as to the effect of holding-devices on the results of crushing-tests.

In crushing-tests, which are usually made on short prismatic pieces placed between parallel platens of the testing-machine, the end surfaces act upon the body by opposing frictional resistance to increase of section. A cylindrical test-piece of low steel (Flussei-

sen), for instance, while shortening $= e = l_1 - l$ (Fig. 62) would not retain its cylindrical shape, according to the considerations stated in (*55*), and have a diameter, assuming that the stress is not above the elastic limit, and volume remaining nearly constant,

$$d_1 = d \,.\, c_f = d \,.\, e_1 \frac{1}{m}$$

and $$v = d_1^2 \frac{\pi}{4} l_1 = d^2 \frac{\pi}{4}$$ or

$$d_1 = \sqrt{d^2 \frac{l}{l_1}}$$

The stress $-S$ acting toward the axis of test-piece, resisting the effects of friction produced by the pressure of platens on the end surfaces, causes it to assume a barrel shape having volume V, in such manner that the increase of diameter is considerably less at the platens than at the centre of the body.

The distribution of stress might be discussed in this case, as was done in (*101*) under similar conditions in tension-test. But it is probably quite self-evident that it is not possible to make a crushing-test in strict accordance with theory, and without the effect of the holding-surfaces, if the test-piece be shaped as shown in Fig. 63, and without going into a detailed discussion of the effect of shoulders or heads. Hence the crushing-test, any more than the tension-test, is by no means a simple procedure.

a. As Bauschinger and others have demonstrated, bodies subjected to crushing when observed by mirror apparatus show that the amount of crushing varies for different parts of the bodies under identical loads. When studying the elastic behavior of stone prisms, for instance, notably different results are found when measuring on short parts near the pressure-platens, and on similar parts at the middle of length of the test-pieces; even when using short, and again the

greatest possible length at middle of test-piece, slight difference in measurements are obtainable. All of this is due to unequal distribution of stress due to the effect of shouldering.

b. The character of pressure-surface is of material influence on results of the crushing-test. Bauschinger considered this subject repeatedly since 1873 (*L* 2). He demonstrated particularly that the pressure-surfaces must be plane (planed, ground, etc.), and indeed those of the platens as well as end surfaces of test-pieces. The former should be very hard if they should answer every purpose. Soft pressure-surfaces, perhaps produced by intercalation of soft materials, would affect the results of crushing-strength to a considerable and indefinite degree, whenever they are so soft that their yield-points are passed, and they begin to yield (flow) from the centre toward the circumference. When the yield-point of soft liners is sufficiently high, then the body, say an imperfectly finished cube of stone, would fail in almost the same manner as though it had been provided with flat surfaces and uniform bearing; the phenomena of crushing would be quite similar, and the resistance is influenced but slightly.

If the material of the liners, however, has a relatively low yield-point, the shapes of fractures will become very different, and the resistance decreased. This is caused by the change of resisting forces ρ, Fig. 62, which tend to prevent spreading of the end surfaces, as well as by the bursting effect produced by the soft liners acting like a tough liquid, which, filling the accessible depressions, forces the body asunder as though by internal pressure.

By lateral flow of liners the forces ρ may not only become $= 0$, but their direction may become reversed and thus produce a considerable decrease of resistance. "Hence it may happen (says Bauschinger) that lead liners cut from the same sheet may in one case in no way change the crushing re-

sistance of a soft sandstone, may slightly reduce that of a harder and stronger sandstone, or a rather soft limestone, and that of a granite very considerably, as much as one half, with the invariable formation of pyramids in the first case, in the second pyramids or these mixed with slivers, and the third case always a fracture composed entirely of slivers. In the latter cases the resistance to crushing is, as a matter of course, to a certain degree more or less independent of the height of test-pieces." (*L* 2, Vol. 18.)

4. Yielding (Flow) Phenomena During Deformation.

106. Upon reaching the yield-point, or inmediately thereafter, especially in case of metals, very regular and peculiar phenomena frequently appear, which may be shown to be partly due to effect of holders (*3*).

In the tension-test, for instance, "scaling" takes place, when testing an iron rod in the condition in which it leaves the rolls (without removal of mill-scale), the instant yielding commences. This layer of scale has a lower extensibility than the metal itself, and hence breaks off as soon as its extensibility is exceeded. Scaling as a rule commences at the heads and progresses toward middle of test-piece; in the case of flat bars the progressing zone usually forms an angle of 45°–60° with the axis of bar.

A polished bar of iron or one having a dull fine-emery finish assumes a matt surface upon passing the yield-point, while a hard, slightly extensible bar (cast iron or hard steel) does not change the appearance of its surface but slightly, and remains bright. The matt surface appears as though covered by a slight breath or dew. Generally the dulness grows gradually more marked, the surface assumes a crinkled or scarred appearance, which finally changes to long wrinkled bodies parallel to the axis of bar, or to longitudinal grooves or folds or crumpling, in the case of uniformly soft materials (soft low steels, copper, etc.). In other metals the

surface assumes a very irregular, peculiar, crumpled appearance.

Similar phenomena also become apparent in the crushing-test.

It is practical and materially facilitates mutual understanding by acquiring the habit of uniformity of diction in speaking of similar and constantly recurring phenomena in reports and publications. For this reason the phenomena here referred to are illustrated on Plate I, and their descriptive appellations, customary in the Charlottenburg Laboratory and partly adopted by others, and generally used in large circles, are here given.

The commencement of loss of lustre and formation of very fine scars is called: the bar becomes "crinkled" (krispelig) (Figs. 1 and 2, Plate 1). When the granules become more pronounced the bar is said to be "scarred" (narbig); grooves or folds are developed (Fig. 9, Plate 1); it becomes "crumpled" (Fig. 64).

107. In case of metals, especially when used as polished strips, other extraordinarily characteristic phenomena frequently arise, so-called flow- or yield-figures (stress-lines). These phenomena are of greater importance for the subject here discussed, because they also afford a view into the operation of holders, and show convincingly that distribution of stress in tension and crushing test-pieces is by no means as simple as is frequently assumed to be the case. A close observation and study of these phenomena does not only lead to interesting theoretical investigations, but it is also of practical importance in the art of testing materials, by shedding light on many occurrences when making measurements of precision, which would otherwise remain unappreciated. Knowledge and observation of these phenomena may also be of very great practical value, because similar effects may sometimes be found on overloaded members,

and may serve as a caution, or a proof of the particular manner of overloading.

Various forms of such yield-figures or stress-lines are shown on Plate 1. Attention should, however, be called at this time to the fact that they do not occur in tension-tests and crushing-tests alone, but are also noticeable in all other tests of strength, and that certain conclusions, drawn from the observation of this behavior of metals, may also be applied to other materials, in which yield-figures or stress-lines do not seem to appear.

108. Several groups of yield-figures or stress-lines may be identified in the tension-test, which have been named in the Charlottenburg Laboratory for purposes of concise diction and identification.

As a rule (in case of flat strips of low steel), one group of figures, beginning at the shoulders, makes its appearance, which are first indicated by a narrow pointed bar or ray, originating at the fillet (in case of square shoulders, Fig. 15, Plate 1), crossing the broad surface of the bar at an angle of about 45°. Other similar pointed rays or lines follow this in more or less regular intervals, at right angles to the axis of bar, their ends frequently returning in the direction about 45° to the axis (Figs. 14–20, Plate 1).

During the further progress either a network of these lines is formed, intersecting almost at R.A., frequently of great regularity (Figs. 3, 14–20), or the lines, emanating from one corner of the bar, forge ahead at an angle of from 45°–60° parallel to each other from the head toward the middle of bar (Fig. 5), line upon line forming, always separated by unchanged narrow strips of the surface of the bar. These separating strips of surface are then traversed by more or less regularly separated lines, at right angles to the bar-axis (Fig. 15).

The phenomena just described probably are the rule:

they are also the cause of scaling previously mentioned as occurring in zones, at angles of 45°–60° to the axis. This phenomenon in its entirety is called diagonal lines or network, because of its essential characteristics; the network is described as close- or open-meshed.

109. Occasionally bands predominantly at right angles to bar-axis appear, which either start from the edges (edge-streamers), Figs. 6 and 10, Plate 1, or develop from the occurrences previously described, and distinctly take the shape of cross-bars or -lines, Fig. 6.

These figures and lines usually disappear entirely in later stages of the test.

110. It is possible to make these figures very distinctly visible on iron if, as was done by Pohlmeyer, the surfaces be carefully polished and then Bower-Barffed, by immersing the red-hot bars in steam, thus letting these lines appear as silver threads among the scales of blue-black oxide. A book by L. Hartmann* came to my notice recently, which treats in detail of these yield-figures and stress-lines, giving a great number of illustrations, which show the results due to all manner of stress in the form of drawings. Unfortunately, I have not been able to use this valuable work in this treatment of the subject.

a. In a previous section I called attention to the practical importance of evidence of flow in the art of testing, and desire to here give proof of this, by quoting in part, literally, a very praiseworthy study, by Prof. B. Kirsch, unfortunately too little known. This work covers, with the addition of theoretical considerations, the results of many years' observations and experience, secured by those employed at the Charlottenburg Laboratory, and especially by Kirsch, while prosecuting extensive experiments with railway material (*L 122*).

Kirsch writes about as follows (*L 108*):

"The striking appellation 'yielding' (Fliessen) was adopted by Tresca (*L 123*) to express the molecular displacement of portions of ductile materials during the effect of external forces. Kick

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*Also compare Kirkaldy's illustrations of stress-lines in tension-tests of riveted joints (*L 121*).

(L *100*, p. 75) remarks thereto that not only a ductile material may be aid to yield, ' but even brittle materials, when entirely surrounded by a sufficiently strong envelope, which itself is subjected to this deformation, may be said to show molecular flow or yielding, because even such bodies admit of deformation precisely as is the case with plastic materials; even brittle materials may change their shape permanently, without thereby producing discontinuity of their particles' " (*L* 124).

Kirsch thereupon makes 6 propositions relating to procedure of flow or yielding if the machine be operated at a uniform speed as is done at Charlottenburg, producing an extension of 1% per minute (1%/min.). These propositions have been partly discussed above, and will be more fully later on; we can discuss in this place only that which belongs in this section.

b. In proposition 6*c* attention is called to the fact "that yielding in general begins at the shoulders," and that this can be frequently proven by determination of differences of width at the yielded and unyielded parts, which sometimes amount to .0147–.0156 in. in a width of 1.56 in. (0.03–0.04 cm in. 4.0 cm).

c. Proposition 6*d* reads: "Yielding is of course most readily observable by mirror apparatus. The following remarks refer exclusively to the use of the Bauschinger mirror apparatus. Several minor details must be considered in order to obtain a clear idea about the (apparent) action of the scale-readings. Thus the inertia of the balance-weights and the staunchness of the piston-packing of the machine may affect them. For before any yielding takes place, and a certain load is applied, a leak at the piston will cause the lever to drop slowly, without yielding of the bar. The inertia of the descending weights produces a slight unloading, a slight retrograde motion of the mirrors, until the scale-pan of the beam takes a bearing, whereupon, after a sufficient interval of time, the bar is unloaded to an extent equal to the friction of the receding piston. Hence if the piston-packing is not absolutely perfect, an accurate observation of the beginning of yield, by the beam alone, is not possible. If the beam be again brought to a position of equilibrium, the magnification of load below yield-point due to the inertia of masses is harmless, i.e., without influence on the direction of readings, when made after the beam has become quiescent. When the load is, however, just below the yield-point it is not an uncommon occurrence that the actual increase of load due to inertia of moving masses produces a stress beyond the yield-point; the bar yields slightly while balancing the beam, and no further change occurs when equilibrium is reached, because the actual stress will then be below the yield-point. Should the beam again drop because of leakage, and then be raised to equilibrium, the bar will again yield slightly. This can be repeated 5 or 6 times, always

stretching the bar slightly. When the packing is absolutely tight, and the stress has just exceeded the yield point, the beam must drop slowly, after having been balanced, immaterially whether the bar stretches within or without the gauge-marks ; the mirrors, however, must at the same time act very differently from the case in which the piston leaked, and the following case will be noted :

1. Both readings increase ;
2. Both readings decrease ;
3. One increases, the other decreases."

d. "In the first case the bar yields between gauge-marks, and it is the custom in the Charlottenburg Laboratory to note on the test reports the passage of the yield-point, when in a given time, say 1 min., having regard to accuracy of readings [0.00078 in. = 2.10 — ⁴cm] a visible increase is noted."

e. In the second case the bar yields without the gauge-marks. In this case an interesting observation may be made. The beam may still be balanced a small number of times when the increments of loads are not too large, before yielding occurs within the gauge-marks and spreads over the gauge-length. Keeping the beam balanced by a relatively slow motion of the piston, there will be no equilibrium between the internal stresses and the uniform tension load applied at the movable end of bar, indicated by the balance-weights on the lever. The part of load actually carried by that part of bar within the gauge-length is therefore less than that indicated by the poise-weight. The extension of the gauge-length must hence be less for the last increment of load than for the same increment of load below the yield-point."

"Table 9, on page 92, shows this very plainly :

f. The third case, in which one mirror shows increasing readings, while those in the other decrease slowly, and in fact while the beam is kept floating, still remains to be discussed. This is the most frequent case. Upon waiting a sufficient length of time it frequently happens that the procedure is reversed in such a manner that the mirror which just gave increasing readings remains stationary and then retrogrades, while the other reverses and gives increasing readings. Still later a moment arrives in which both reflected scales advance rapidly. These occurrences are readily explicable when remembering that yielding progresses in a diagonal direction (Plate 1, Fig. 5). In case the yielding zone *ab*, Fig. 65, has advanced its leading point to within the gauge-mark, the right-hand mirror will show increased readings, while the left side of the bar *L* is still only yielding without the gauge-mark. This irregularity causes the bar in the first place to move bodily to the right hand, and the entire mirror apparatus revolves about the knife-edge *e*.

Table 9. Yielding without the Gauge-marks.*

Load. L kg	Stress. S atm.	Scale-readings. Left $\frac{1}{50000}$ cm	Right $\frac{1}{50000}$ cm	ΣA cm 10^{-6}	ΔA cm 10^{-6}
1	2	3	4	5	6
		A calculated for $S = 0$		− 60	
250	80	0	0	0	—
1000	320	105	75	180	180
2000	640	221	185	406	226
3000	970	342	290	632	226
4000	1290	468	390	858	226
5000	1610	594	490	1084	226
250	80	22	12	10	—
5000	1610	611	477	1088	—
6000	1930	734	577	1311	223
7000	2250	855	681	1536	225
8000	2570	970	790	1760	224
250	80	18	3	15	—
8000	2570	964	800	1764	—
9000	2900	1070	918	1988	224
10000	3220	1155	1060	2215	227
11000†	3540	1200	1235	2435	220
12000	3870	1210	1444	2654	219
13000	4182	1240	1620	2860	206
13250	4270		Yielding		

* All figures given in metric measures.
† Stretches, readings decrease (yielding without).

"Both motions produce a decreased reading in the left and increase in the right mirror; that the reading of left scale must actually be retrograde is at once explicable by the fact that the gauge-length, as long as b remains without it and the beam floating, is constant; in fact, a decrease of stress on side L may take place during the progression of point b, and a consequent more rapid yielding, again producing decrease. The reversal of mirror motion * from right ahead, left back, right back, left ahead, is explained by the fact that yielding under head at ab ceases temporarily, instead of which a similar yield-zone, as cd, advances from the opposite head into the gauge-length."

* In case of round bars the oblique direction frequently only causes a progression or recession of the apparatus, i.e., increase or decrease of readings, because yielding may occur in any plane with relation to the axis.

"In case of rapid progression of both mirrors, either the entire front edge of zone has advanced into the gauge-length or both point *a* and *d* advance simultaneously; at any rate it is certain that the gauge-length is yielding when one mirror gives rapidly increasing readings (with floating beam !).

g. Kirsch appends a theoretical discussion on the relation between yielding and stress, to which I wish to refer the reader, because he there gives several very interesting points of view. These considerations lead to the conclusions, when using Mohr's method of illustrating the effect of forces acting on one point of mass, "that yielding of solid bodies is due to the fact that the resistance to shearing Ss_M is overcome at the point where yielding takes place, and that the tenacity S_M is overcome at the ruptured section at the instant of rupture."

111. These superficial more or less similar yield or flow phenomena, above described, sometimes permit drawing deductions as to the anterior treatment to which the material had been subjected, and in fact occasionally indicate it directly.

A flat strip of low steel, for instance, which has received several isolated hammer-blows for the purpose of straightening before filing, traces of which can no longer be seen thereafter, or if a lateral pressure had stressed it locally beyond the crushing-limit, these points again become evident during yielding. Centres of stress-lines are eventually formed, from which they radiate with more or less regularity, similar to the effect of shoulders.

The particular spots are less yielding than the surrounding material; they therefore appear in relief, and retain larger dimensions than those assumed by the yielding material. (Plate 1, Fig. 11.) Punched or rolled marks, or the serrations of vise-cheeks, can be made readily visible. (Plate 1, Figs. 12 and 13.) Flat strips, cut from the flanges of rails, previously subjected to the bending-test, plainly showed during tension-test the points at which they took a bearing on the rollers during the bending-test. (Plate 1, Fig. 11.)

Fig. 7, Plate 1, also shows yield or flow phenomena, determined by initial treatment of the material, and have been described by me as follows (*L. 122*, p. 2):

"Moiré. This term has been temporarily used, for lack of a better or more concise expression, to denote appearances of very nicely polished flat strips cut from rail-webs and flanges. They are very delicate markings, which resemble the bands such as are found on the well-known textile fabric known as "Moiré antique." These markings are produced by the effect of the rolls on the material, due to yielding while rolling, which is similar to yielding under effect of tension stress, the molecular mobility not being uniform. After leaving the rolls and during cooling, the non-homogeneity produced is not entirely eliminated; hence they will reappear during the tension-test and affect the mobility of particles when yielding occurs. As a result these markings appear on the surfaces, and the less yielding parts will be in relief, while those more easily yielding will form depressions. The irregularities of the surfaces of the rolls also play a part in this procedure, because the elevations produce more rapid flow of the metal, because of the greater pressure, while the depressions exert less pressure, and hence produce less rapid flow under the rolls; the most severely pressed parts will appear in relief on the polished surfaces during yielding."

112. The value which the study of yielding during tension-test may have is also readily shown by the instances above discussed, for it is plain that bars showing such local phenomena cannot develop the complete ductility of the material, and must therefore lead to an unfavorable opinion. At this stage it must already be very apparent that the preliminary treatment of material, to which it is subjected before cutting off the test-piece, is of great effect upon the results of tests.

Many observers have heretofore called attention to superficial yield or flow figures, but what has been said will no doubt suffice at this time.

5. Contraction.

113. If the tension-test of a soft and ductile material be carried beyond the yield-point, local contraction will take place at one section before rupture, as previously stated (*44*), because the material yields more rapidly at that than at other cross-sections at which the material then remains quiescent. The adjoining parts of the bar, so to say, take the place of shoulders, by opposing a resistance to contraction. When operating the machine, as has been heretofore assumed to be

the case, so that extension is equal for equal intervals of time, the load L must decrease after passing the maximum, to produce equal extensions, and this is the period during which contraction usually takes place. Because of the rapidly changing forces and cross-sections, whose mutual relation during test it is exceedingly difficult to determine continuously, it is not possible to obtain an entirely clear conception of the conditions of stress during contraction.

Barba (*L 105, 118*) tried to obtain a conception of the true inwardness of contraction by the following argument:

He imagines, as in Section 101, the bar to be subdivided into its component elements (fibres), and considers that the external fibres having assumed greater length, because of their shape, than the centre fibre, which remained straight, they must also be subjected to greater stress and rupture before the others. It is, however, a fact that rupture always begins at the middle fibre. Hence the external must affect the interior fibres, which causes maximum stress in the latter. He attempts to explain this as follows:

114. The element A, Fig. 66, of an outer fibre is acted upon by two equal but opposed forces p, at an angle with each other equal to the curvature of the fibre. In order to establish equilibrium there must be a force p_1 in the adjoining particles acting on the element A, which is equal to the resultant between the two forces p. Analyzing the entire section in this manner, it will be found that the middle fibre is subject to the sum of reactionary forces p_1, whose components p'', because of symmetry about the axis, counterbalance each other, while the components p' are added together, reacting against the stress S produced by tension loading or coacting with it, according to the shape of curvature of the element under consideration.

From this it will be seen that the middle fibre is subject to minimum stress (smaller than S) at the beginning of contraction, that the middle fibre has a stress equal to S at that section where contraflexure of fibres is found,

and that stress of middle fibre is greater than S at the centre of contracted section because of the reversal of direction of component p', and hence that fracture must originate at the centre.

115. That this is the actual occurrence during rupture can be readily seen by trying to join the opposite ends of a fracture of a rectangular test-piece. Bars having a very large contraction always gape more or less at the centre. [Gollner, among others, illustrates such fractures in "Technische Blaetter, 1892."] Howard (*L 125*) found that in case of bars of great contraction, tested under high temperatures, it was clearly shown that rupture was not sudden, but originated at the centre, gradually extended to the outer fibres. When continuing a test to 800° C., until 94% contraction had been attained, and then stopping and filing the skin at the narrowest point, a cavity was found to exist in the centre of the neck.

116. Many writers have covered the surfaces with a network of lines or circles in order to obtain a representation of distribution of stress during tests, studying their deformation during them or after rupture. It will be found after rupture that these lines will have been so displaced near the point of rupture that the adjacent space, Fig. 67, $aa_1 < a'a'_1$ (omitting the gap), while the reverse, $ab > a'b'$, is true in the following spaces, which would correspond with our deduction. Barba (*L 118*, Plate 8) also shows test-pieces scribed with such network, and describes them exhaustively in that paper.

6. Fractures.

Tension-tests.

117. The appearance of new fracture is often of particular importance in judging of the quality and technical applicability of materials. Hence it is necessary to append to all reports of tests a most readily comprehensible description of shapes of fractures and of character of surfaces of rupture. Al-

though it is not possible to describe typical fractures of all materials at this time, the most important characteristics of those of metals will be here shown, because it will lead us one step further in our knowledge of the distribution of stress in the test-piece, and emphasize the necessity and value of uniformity of nomenclature.

As some of the characteristics of fractures are not due to the quality of material, but rather depend upon the method of producing rupture, or may be ascribed to the accidental external shape of test-piece, the latter mainly shall be now discussed, while those depending upon special peculiarities of the material will be treated of further on.

118. The greatest contraction is found in very tough and soft materials, such as lead, tin, pitch, yellow hot iron, etc., and the least contraction in brittle materials, such as glass, hard steel, cast iron, stone, etc.

In very tough materials, round bars are drawn down to points, flat bars to knife-edges, bars of triangular or rectangular section assume a cruciform shape, as shown by heavy black lines in Fig. 68.

In very brittle materials change of shape of section is hardly noticeable; the dimensions are merely changed a trifle. Between these two limiting types there is gradation of infinite variety. Generally the fracture of the round bar shows a circular smooth ground surrounded by short pinnacles. When this fracture is most perfectly developed a projecting crown or ring will be seen to completely surround the flat surface of one part of the fracture, while the other will be a truncated cone, Fig. 69. The imperfect edge, pinacles, in Fig. 70, corresponds with this formation. It proves that absolutely perfect fracture produces three parts, namely two truncate cones and a surrounding ring or crown, Fig. 71. The flat surface or ground of fracture is, however, larger or smaller, depending upon peculiarities of the material. Occasionally perfect cones and cups, Fig.

72, are formed, while in others there is but the slightest trace of a crown, Fig. 73. These are called "cup shapes" (of course considering the cone as a part of it), and rim or crown shape; it is also called cup with flat bottom (Plate 2, Figs. 9, 10) when the funnel shape is the greater part of the fracture; or it is styled fracture plane, with rim, when the flat ground is predominant. Rim pinnacled (Plate 2, Fig. 18) or toothed is applied to fracture in case the rim is left partly on both fractured surfaces. It also happens that one half of the crown remains on each part of the fracture, Fig. 74, and that the ground is very small. Another form is shown in Fig. 75, in which the funnel shape has almost entirely disappeared, and is often hardly noticeable under a cursory examination.

[In the United States and Great Britain these distinctions are unfortunately not clearly drawn, and mainly because comparatively little attention has been paid to these various shapes as indicating definite causes. They are all called "cup shapes" in a loose manner, as follows: Fig. 69, perfect cup; Fig. 70, broken cup; Fig. 71, no name because rare; Fig. 72, deep cup; Fig. 73, slight cup; Fig. 74, half cup; Fig. 75, oblique fracture. As these appellations are not sufficiently descriptive, I propose to name the fractures shown in Figs. 69–75 as below, retaining the name "cup shapes" for the entire group; for although it is not a characteristic term, common use warrants its retention; a cup has a very indefinite shape, while funnels or cones have shapes following definite laws, just as do fractures of materials. Hence I shall name fracture as shown in

Fig. 69. Truncated cone, or do. pyramid.
" 70. Pinnacled cone " " "
" 71. Double cone and crown or do. pyramid.
" 72. Perfect cone, " " "
" 73. Fin cone, " " "
" 74. Half-crowned cone, " " "
" 75. Sheared cone, " " "

In case of test-pieces of rectangular section the shapes will be pyramids instead of cones, other characteristics being the same and following the same laws.

When a secondary cone or pyramid forms in the ground or top of truncated cone or pyramid, then the fracture may be defined by adding the word "compound."

Translator's Note.—G. C. Hg.]

119. The last fracture is frequently formed on flat test-pieces, in which, however, the cone-funnel shapes (Plate 2, Figs. 1–8) are as pronounced as in the case of round bars, only somewhat modified, Fig. 76. Rims or crowns, concave on the long flat sides, and convex on the narrow edges when certain proportions between width and thickness obtain, correspond to the contour of fractured section and the final shapes of soft materials shown in Fig. 68*d*.

Attention must also be called to another peculiarity of contraction of flat bars. In greatly contracting material the so-called contractile cross is formed, and in such manner that the thickness is a minimum on the lines *aa* and *a'a'*, Fig. 77; it is therefore less at *a* and *a'* than at *b*.

The descriptive terms as in case of round bars are also used for flat bars. In case one half the rim adheres to part of fracture, Fig. 76, it is usually described as "fractured oblique to axis," although, speaking accurately, this should not be done, because it may lead to the idea that a different type is referred to, while in fact it is a perfectly normal funnel-formation (pyramid) even when the flat ground can hardly be recognized.

In foregoing Sections 101–104 and 106–110 it has been repeatedly mentioned that distribution of stress in a bar under tension cannot be a simple matter.

a. This will be readily recognized when examining the normal phenomena of fractures and fractured surfaces carefully. These conical or funnel-shaped surfaces in case of round bars, starting from the shoulders, their apices pointing toward the axes, indicate surfaces of maximum shearing strains in uniformly homogeneous

materials. These cones, starting from the shoulders, with their apices lying in the axis of bar, penetrate each other, as shown plainly in Fig. 78.

b. Kirsch attempted (*L 108*, 1889, p. 11) to demonstrate this conception and cone-formation. He tried to establish the fact that rupture originates at the axis in the contracted neck, and thence spreads over a circular area, to form the ground of the funnel or apex of truncated cone, whence, following the planes of equal (maximum) shear, it produces the sides of cones or funnels ; hence the tension-stress S is overcome at the central plane area, and the shearing-stress S_s at the conical surfaces. The relative amount of production of one or the other effect is dependent upon the peculiarities of the material.

Occasionally reverse cones are found distinctly developed in the fractured surfaces, the principal cone forming on one surface, while a smaller secondary cone formed on the opposite surface is pulled out of the apex of the primary cone. Such a fracture is shown on Plate 2, Figs. 6 and 7.

120. Aside from the shape of a normal fracture, its superficial appearance is especially characteristic of the manner of applying stress to the test-piece, and for this reason the typical characteristics cannot be impressed upon the memory with too much sharpness, because it is frequently possible, without regard to actual tests, to determine causes of failures of machines by the appearances of surfaces of fracture. But there are other reasons why no opportunity should be neglected to study the appearances above described, and especially those to be discussed later on, with the use of samples, because they cannot be fully explained by descriptions and illustrations. Where there is opportunity of making numerous tests, collection of fractures, carefully arranged according to typical forms, should be made. This is all the more necessary, because it is customary in practice to ascribe fractures to non-homogeneity or defects in material, which are positively consequences of method of testing or due to distribution of stress during test, and can by no means be considered as defects of material.

Based upon such collections, it is easy to establish a uniform descriptive nomenclature of fractures, and it is very much to be desired to attempt certain uniformity, as this secures brevity and more general comprehensibility.

It is by no means easy to establish a good and really valuable nomenclature of fractures, and hence not only was a well-arranged collection of fractures made at the Charlottenburg Laboratory, but, in view of frequent changes in the personnel, a special set of rules for describing fractures was introduced. (*L 122*, p. 22 and preliminary notes to Tables.) According to these the following order is to be preserved: Color, grain, sheen and lustre, structure, fracture type, defects, and the names previously and hereafter used and printed in open type are customary.

121. The ground, centre, or top of fractured surface (in metals) can be more or less flat. If it is irregular, it is also usually dull or has a mat appearance. This is generally due to the fact, aside from peculiarities of material, that very numerous minute funnels or cones are formed on the plane, Fig. 79. If the material, such as steel, low steel (Flusseisen), etc., have a crystalline structure, the ground will be crystalline, and as a rule duller at the centre than at the circumference, where brilliant points are frequently found (as in low steels—Flusseisen, etc.) even when the ground is otherwise mat. The dark core in the centre is frequently quite clearly defined. It is customary to designate these descriptions appropriately as: Ground mat, or brilliantly crystalline, with darker or mat core, etc. Plate 2, Figs. 11, 12, 15–17 show such fractures.

122. The funnel surfaces (inner rims) always have a more or less rough, pinnacled, invariably somewhat brilliant surface; an appearance which later on will be recognized as characteristic of sheared fractures.

Very frequently finer or coarser radial rays, Fig. 80,

will be seen on the ground, which are also consequent to certain happenings during the tension-tests, and the cause of which cannot be explained until later on; at present attention is called only to the following: The rays do not always originate at the centre; they sometimes radiate from an eccentric point, Fig. 81 (Plate 2, Fig. 14). In this case careful examination of the fractured piece at the centre of radiation will almost invariably discover a defect in the material which was the cause of rupture at that particular section. Radiation always proceeds from that point at which rupture originated. For this reason these lines are called fracture-lines at the Charlottenburg Testing Laboratory (Plate 2, Figs. 11, 14, 16, 18 and 19).

Another type of fracture, the cause of production of which is not yet accurately known, is shown in Fig. 82, and consists of radiating ridges, one side of which is usually vertical, while the other is inclined to the plane of the ground (Plate 2, Fig. 13). Heretofore these rays were usually called coarse-fracture lines.

a. These last-named types, the strongly developed cores and other phenomena, are in practice frequently considered as defects. Caution must, however, be had in this respect; they are usually peculiarities developed by the regular structural arrangement. This will be easily understood when studying them by means of collections of fractures arranged according to types. It will thus be seen that fracture-lines and cores will be developed in cylindrical test-pieces, equally symmetrical to the axis, when the pieces have been cut either from the edge of an ingot or from a round bar rolled down from a large bloom. In the latter case it might be considered that the coarse fracture-lines (Fig. 82) are nothing else than remnants of the porous zone in an ingot.

For if such a porous ingot (Fig. 83) be rolled down into a round, the blow-holes are drawn out in the direction of rolling, they are flattened, and these flattened walls may arrange them-

selves radially and symmetrically to the axis. When fractured, such porous bars show sharply cut (fissured) surfaces, vertical to the plane ground. Generally, however, the adjoining oblique surfaces are wanting. As a rule, the lines and surfaces produced by blow-holes can be readily distinguished from those described above as "coarse fracture-lines."

b. Kirsch (*L 108*, 1889, p. 15) thinks he can explain the coarse fracture-lines as follows:

"When the material is very homogeneous, such as low steel (Flusseisen) or copper, the elementary funnels [K. assumes that the ground-surface of the fracture may consist, conditionally, entirely of funnels lying adjacent to each other, *121*] may group themselves in very different ways into complete oblique surfaces of fracture. In addition to the element of a funnel passing through a point, there are two additional elements of surface which have the same shearing stress and are vertical to each other and also to the element of the funnel. The total of these elements of surface form two groups of helicoidal surfaces, which are coaxial with the bar, intersecting its surface in helical lines. The helical lines are frequently developed in tests. In Plate 2, Fig. 24, the fracture end of a bar of copper is illustrated, which shows, beside the double-funnel formation developed on one side of the fractured surfaces, two such clearly defined helicoidal surfaces, which in fact extend for a considerable distance into the bar, forming separating surfaces.* The fracture-surface shown in Plate 2, Fig. 13, of low steel (Flusseisen) shows these helicoidal surfaces at their projections and their radial arrangement very clearly. (Kirsch refers to the oblique [helicoidal surfaces] which were described above, Fig. 82, as coarse fracture-lines.) Such

* I have scratched one of these lines slightly with a scribe, as far as it was visible, as otherwise both lines could not have been shown by photography.

fractures also regularly show separating planes passing radially through the axis of the bar."

123. Aside from the phenomena occurring on the surface of metal bars of homogeneous structure, immediately after passing the yield-point, and aside from crinkling, wrinkling, crumpling, etc. (*106*), there appear in steel and iron, etc., transverse fissures, arranged in quite regular series, the appearance of which is again a proof for the views relating to the formation of cones and funnels previously explained, and is therefore briefly referred to here. These phenomena, called longitudinal seams at Charlottenburg, are illustrated in Fig. 84, and Plate 1, Figs. 2, 4 and 8.

In my report on railway material (*L 122*, p. 23 et seq.) I stated:

124. "When a hard spot or grain, etc., is present in a steel ingot it will be stretched lengthwise by rolling, and form a fibre parallel to the axis of rail. If the differences in hardness are great, fissures will be produced during rolling; if they are, however, slight, these hard arteries will hardly be noticed, not even on the end sections of the rails. During tension-tests, however, they appear distinctly even when they are several millimeters below the surface. During yielding the hard veins or the swelling of the material over them is seen. The vein rises above the surface, though but slightly, see Fig. 84*a*. This is a necessary consequence of greater hardness, which causes less yielding than that of the softer body of the mass; the reduction of section of the hard parts is less than that of the softer material; the hard material has less extensibility than the softer. The consequence of these properties is non-uniform distribution of stress. The hard material is subject to greater stress than the soft, because it cannot follow the motion of the mass of the latter." Hence transverse fissures occur in the hard vein, which must follow each other in quite regular intervals, the dimensions of which are dependent upon the relation between the

strength qualities of the hard veins and soft material, and upon the amount of friction at the surfaces of contact of the two materials, as was developed by Kirsch in his discussion (*L 108*, 888, pp. 44 and 45) as follows: "But the soft material as well, will be overstrained locally at the instant of beginning of these fissures, by the motion rapidly taking place; short separating fissures are formed following the conical surfaces of equal shearing-stress. As these cones intersect the surface of bar in regular series, the superficial appearance shown in Fig. 84 is produced. The occurrence of transverse fissures often manifests itself during the test by crackling or metallic ring, even when the fissures are not externally visible."

That these longitudinal seams and the hard veins do not always necessarily form dangerous parts of the material I have explained in the further considerations of the paper above mentioned (*L 122*, p. 26). On another occasion (*L 126*, p. 60 et seq.) I instanced a case which showed the dangerous influence of fine transverse fissures in material very clearly, being a cast-steel wire which had countless internal cavities at regular intervals.

Crushing-test.

125. When a cylinder of brittle material, such as marble or cast-iron, is caused to fail by crushing, the fracture shown by Fig. 85 is usually produced. Pressure-cones are developed at the platens, which can be readily seen in the fracture, provided it is possible to protect the pieces against impact due to the elastic recoil of the testing-machine. Similarly as in the tension-test two cones and a surrounding ring *R* are formed in the crushing-test, which, however, rarely remains coherent in large pieces; in the tension-test it adheres wholly or partly to one half of the test-piece; during crushing-test it is more or less demolished and thrown off.

126. Occasionally, especially when the heads of the machine have a slight lateral motion, the two halves of test-

piece are pushed laterally upon each other during the crushing-test, as in the tension-test, and produce f r a c t u r e o b l i q u e t o t h e a x i s, Fig. 86. Frequently fissures are also found on the envelope of the cylinder, especially in the latter case, which are more or less regular and cross at angles of 90° (45° to the axis of body).

127. In cubical bodies of brittle material, as stones and cement, pressure-cones are replaced by p r e s s u r e - p y r a m i d s, and the enveloping ring is similarly shaped. It is recognized that the friction of the platens prevents spreading of the material at the pressure-surfaces and bulges above them, forming pressure-pyramids and bursting the enveloping ring.

During this occurrence the envelope is more or less subject to tension-stress, and in such manner that the element of mass A, Fig. 87, subject to the crushing-stress $-S$, becomes subject to tension-stress S because of the bulged form. These stresses produce diagonal fissures as soon as the components τ of forces S and $-S$ become so large that they exceed the shearing resistance of the material; a component τ at right angles to the line of fissure shown is also developed, producing other fissures intersecting the first at an angle of 90°. When the tensile resistance in the direction of the circumference of test-piece is small, as is the case in fibrous wrought iron, the tensile stresses S produce surface-fissures parallel to its axis.

128. It can be proven that the material in contact with the platen remains almost quiescent even when it is very ductile, by building up a body out of several layers of, say, lead or differently colored layers of clay to form a crushing test-piece. After test a section will reveal that the two outer layers are planoconvex, and the central double concave, Fig. 88, and also how the individual layers have been forced outwardly. The volumes of the separate layers have remained constant when a material of density 1 has been used.

7. Determination of Extensibility.

a. Method of Measurement.

129. The conditions under which changes of shape are determined may affect the results of measurements, regardless of the errors of instruments. At this place the influence which these conditions may have upon the determination of the important final permanent deformations, having practical value as a measure of quality of materials, shall be examined. These discussions shall refer, it is here prefaced, exclusively to the tensile-test, and essentially to soft and relatively extensible metals, which fail with more or less distinctly marked local contraction. Permanent shortening after failure, during crushing-test, is only of subordinate practical value, because it has rarely thus far been used as a measure of quality in judging materials.

130. As will be shown in a later chapter (*b*), the original length l_g, the gauge-length, on which the extension after rupture (the permanent extension after rupture) is measured, exerts an effect upon the result of such measurement. For this reason it was soon agreed, either quietly or upon consultation, to adopt definite dimensions for the gauge-length l_g. At the present day the gauge or standard lengths of 8 or 4 in. (= 20 and 10 cm) are in common use in industrial countries; the most generally adopted length being 8 in. (= 20 cm). The prismatic part of the bar, or finished length, l, is usually somewhat greater.

131. It is still largely customary to determine extension after fracture by measuring the change of gauge-length l_g between two scribe- or punch-marks, upon abutting the two parts of the broken test-piece against each other. This extension, expressed in % of gauge-length, has been designated (*14*, *37*) ultimate elongation or elongation e% of the material.

This method of measuring extension, much used in practice,

is, however, subject to notable errors, independent of the errors of instruments used, which must be designated as errors of method. They should be avoided to prevent injustice to one's self and to others.

In Sect. 115 it has been emphasized that fractured ends of flat bars do not match or fit perfectly, but gape noticeably at the middle, especially in soft material; even round bars no longer join neatly. Hence this method invariably produces excessive values of elongation.

132. In order to decrease this error it has been proposed to provide scribe-lines or punch-marks on a line on the sides of test-pieces and then to add the measurements of distances from these marks to the points of fracture on the line, and to determine the elongation $e\%$ from this sum.

This would of course obviate the above error, but the method still used in practice leads to other errors as well, which are, especially in soft metals such as low steel (Flusseisen) and copper, essentially more important, and must invariably be uniformly unfavorable to the producer, because they always make the elongation appear too small.

133. In Sections 100 and 113, while discussing the effect of heads and shoulders and of contraction, convincing proof was obtained that elongations of different parts of bars are very markedly different according to their distance from the point of rupture.

The inappropriateness of the common method can thus be readily adduced.

In order to give a comprehensive view of this fact, I shall here reproduce a part of my report on the investigation of copper (*L 110*, Pl. III, Fig. 36). In Fig. 89 a series of diagrams of elongations are reproduced, which give the elongations of individual divisions of test-bars of equal section (rectangle $a = 1.0 \times 3.0 = 3$ sq. cm) rectangle $a = 0.39 \times$

$1.18 = .464$ sq. in. In order to obtain these results, the test-bars were provided before test with uniform divisions over their entire length, as is customary in all public testing laboratories. On each of these divisions the extensions were measured after test, and stated in % of original length. The results thus obtained were plotted in Fig. 89. The lines, however, as must not be forgotten, represent test-bars of relatively very short length only; they contain the effect of the shoulders (*104*, Fig. 61).

134. Conceiving these diagrams as relating to a bar of very considerable length, they will assume the general shape shown in Fig. 90, and with this drawing as a guide convincing clearness will be obtained of the influence which the location of fracture with relation to the gauge-marks must have on the measurements of extensibility.

Let aa_1 in Fig. 90 represent the original length, the gauge-length l_g, i.e., 8 in. (20 cm), to which elongation $e\%$ is referred. Evidently the elongation of one part of this length is equal to the mean elongation of all the included parts, and hence measured by the area of diagram over aa_1 whose mean ordinate is $= e\%$. If rupture, however, occurred near one end of the gauge-length, so that the gauge-marks would coincide with b and b_1, the measure of extensibility would then be represented by the hatched area over bb_1, which can at once be said to be smaller than the area above aa_1, for the added hatched area over ab must be less than the discarded area over a_1b_1. It can also be instantly seen that the area over the equal length b, and hence the measured extensibility, must be a maximum when rupture occurs at the centre of length l, and a minimum when occurring exactly at a gauge-mark a or a_1. This will show with convincing clearness that even in the same bar the elongation or extensibility of material must be found of different values, when measurements

are not always made in an identical manner, and then symmetrically to the point of rupture.

If the fracture occurs away from the middle point of the gauge-length, elongation when determined between gauge-marks, as is so commonly done in practice, cannot be found otherwise than too small, and as elongation is used in practice as a measure of quality, the common method of determining elongation invariably injures the interests of the producer.

135. It has of course been attempted to exclude this palpable error of method of measurement, or to reduce it, and this can be effected by the method developed in Sect. 137.

Consideration of the curves given in Fig. 89, obtained from bars of relatively short lengths, will show that, aside from local variations, the curves either side of the point of rupture are almost identical. This proves that the changes of shape of both ends may in fact be assumed to be symmetrical about the point of rupture, which is indeed most likely to be the case in entirely homogeneous material, and has frequently heretofore been quietly assumed to be the case. Essential variations from this rule are only found, besides in the above-indicated accidental cases produced by irregularity of material, in such curves obtained from bars which were ruptured quite close to either gauge-mark, and also close to either shoulder, Fig. 91.

In all such curves derived from actual test the effect of holders previously described (*100*) may be clearly traced when the heavy line in Fig. 92 is conceived as the curve of elongations up to the instant of local contraction; it fully corresponds to the curve previously given in Fig. 51, which shows the influence of holders. The broken line representing contraction becomes tangent to the heavy line (Fig.

92*a*) whenever rupture occurs at the centre of test-piece; and in that case the line actually becomes symmetrical about the point of rupture. As soon as rupture occurs near either shoulder (a_1) symmetry of the curve on either side of it is no longer perfect, because the effect of the near head on shape of local contraction is greater than that of the more distant head, which must in fact cease entirely, because the material between the point of rupture and the more distant end no longer elongates after the beginning of local contraction. The shape of this side of the local contraction must therefore develop exactly as in case of a very long bar. In short, the shape of curve can no longer be symmetrical with reference to the location of fracture, as soon as the latter occurs near one end of bar, as shown in Fig. 92a_1. These variations from true symmetry are, as a rule, not large and may practically be neglected.

136. Under the practically permissible assumption that deformations are symmetrical about the point of rupture there is one method of procedure, which gives accurate values for extensibility of materials under all conditions, excluding the certainly insignificant errors of the assumption.

Conceiving the curve of elongations of a test-bar provided with numerous equal spaces, which broke at point a_1, Fig. 93, near the end of gauge-length l_g, this curve may be considered as extended over the further end $a_1 - a_2$ shown by broken line. In this case the true elongation of the material would be represented by the area over $b \cdot b_1 = l_g$. This can, however, be determined with equal facility from the bar broken unsymmetrically, by filling in the missing part a_1b_1, obtained by measurement of the corresponding part over bc, on the other side of the point of rupture. Hence the true value of elongation is also given by the area over ba_1 + area over bc.

137. In order to carry this method out practically, the

public and scientific laboratories provide tension test-bars with spaces (at present generally centimeters), which are either marked by the double centre-punch, Fig. 94, scribed by a dividing-engine, or by using a special spacing-gauge, Fig. 95. When rupture occurs at any one of these divisions, merely counting the spaces will locate those points which were originally equidistant from the point of rupture, and hence the extension of the spaces missing at the short end, measured from those correspondingly situated on the long end, will supplement the measured extension according to the above-described method. If, as in Fig. 96, rupture occurred between lines 0 and 1, then measurements of

$$(0 \text{ to } 10 + 0 \text{ to } 3' + 3 \text{ to } 10) - l_\epsilon$$

for $\frac{l_\epsilon}{20}$ parts will give e, and hence

$$e\% = \frac{e}{l_\epsilon} \cdot 100 \quad \text{by calculation.}$$

a. The subject of determination of elongation after rupture has repeatedly occupied the attention of the "Conferences for Unification of Methods of Testing of Materials" (*L 128*), and recommended the method described above. On these occasions several other spacing-gauges were proposed, as, e.g., by Prof. Belelubski. The Charlottenburg Laboratory uses simple bars as in Fig. 95, only that a flat strip is attached on one side as shown in section in Fig. 97. This strip insures proper apposition on round bars; the back of it is used to scribe a straight line. The scribing is done by a flat knife-shaped edge tool, the flat side of which is carefully and accurately guided by the serrations of the gauge. In this manner the usual errors of inaccurate scribing are avoided.

b. Flat bars are provided with divisions on both edges. In Charlottenburg the device shown in Fig. 98 is used, in order that marks on the two sides be truly opposite to each

other. It consists of a wooden base provided with two stops *a* and *c*, which insure the relative positions of the bar *d* and the gauge *e*; the guide *b* fixes the position of the other end of bar *d*. Stops *a* and *b* are adjustable in a dovetailed groove in the base, to suit various lengths of bars.

c. In order to determine the possible errors of this method, such a gauge A made to scribe divisions $l_a = .273$ in. (7 mm) was compared with the standard of length by the dividing-engine at the Laboratory, then a set of lines were scribed with it, and these B spaces again measured by the engine. (This test affords students experience in micrometric measurements, and leads to observation of sources of errors, in use of instruments and scales.) These results of measurements are given in Table 10.

Table 10. **Comparison of Spacing-gauge and of Spaces produced l = 0.278 in. (7 mm) with the Bamberg Standard of Length.**

A indicates spacing-gauge; B indicates spaces.

Number of Line.	Distance.	Readings of		Differences of		Residual Error of B
		A	B	A	B	
0	0	0	0	0	0	− 10
1	7	6.97	7.03	− 3	+ 3	− 7
2	14	13.99	14.04	− 1	+ 4	− 6
3	21	21.01	21.09	+ 1	+ 9	− 1
4	28	28.01	28.06	+ 1	+ 6	− 4
5	35	35.10	35.09	+ 10	+ 9	− 1
6	42	42.06	42.09	+ 6	+ 9	− 1
7	49	49.08	49.09	+ 8	+ 9	− 1
8	56	50.11	56.14	+ 11	+ 14	+ 4
9	63	63.16	63.14	+ 16	+ 14	+ 4
10	70	70.10	70.06	+ 10	+ 6	− 4
11	77	77.10	77.06	+ 10	+ 6	− 4
12	84	84.10	84.06	+ 10	+ 6	− 4
13	91	91.17	91.10	+ 17	+ 10	0
14	98	98.23	98.13	+ 23	+ 13	+ 3
15	105	105.18	105.13	+ 18	+ 13	+ 3
16	112	112.18	112.15	+ 18	+ 15	+ 5
17	119	119.22	119.15	+ 22	+ 15	+ 5
18	126	126.25	126.17	+ 25	+ 17	+ 7
19	133	133.33	133.17	+ 33	+ 17	+ 7
20	140	140.26	140.19	+ 26	+ 19	+ 9
			Average difference of B = 10.2			

Examination of series of errors A and B shows the variations to be nearly all positive and almost identical with reference to the standard bar. A cumulative error was not found (the divisions of the gauge were copied from a screw). As the reading of the o line must also be considered as containing errors of observation, i.e., the reading and difference o is not to be considered as having greater importance than all other numbers, the actual errors of divisions B are obtained by deducting the mean error of B (+ 10.2) from all individual errors of B, the same as though shifting the spaces with relation to the scale in such manner that all dividing-lines coincide as nearly as possible with the actual lengths. The errors then still existing (last col. of table) appear positive and negative, having maxima which do not exceed 0.004 in. (0.1 mm). The error is usually very considerably below this value.

The measurements of the test-bar are, however, usually made directly by scale or by dividers, according to conditions, and are rarely more accurate than 0.008 in. (0.2 mm). Hence scribing spacing-lines on test-bars by means of a spacing-gauge, which method is in general use, is done practically with sufficient accuracy when the gauges are sufficiently accurate.

e. The above-mentioned "Conferences" have, however, considered the question of measurement of extension in other ways. It is known that rupture originates at the centre of bars, as explained in Sect. 115, and that extension of flat bars near point of rupture is greater on the narrow edges than at the centre-line of the wide faces. In accord with this fact the Berlin Conference adopted the resolution of v. Tetmajer "That elongation of flat bars be determined from measurements of extension of series of equal spaces on both narrow edges (as had been and is now mostly customary at the Charlottenburg Laboratory) and on one wide face."

As a matter of course I introduced this method in the Laboratory immediately upon adoption of the resolution. Although the additional labor is in many cases hardly worth the trouble, the increased certainty of the threefold independent determination of the same factor is sufficient reason for its adoption in official testing laboratories. It is, however, valuable, for practical work, to obtain certainty as to what extent simplification of methods of measurement may be carried without obtaining very erroneous values of elongation. I therefore here communicate a tabulation of measurements of copper flat bars 0.273 × 0.82 in. (7 × 21 mm) in section, Table 11.

Table 11. **Differences of Elongation of Edges and of Faces of Copper Flat Bars.**

Ultimate elongations in %, measured on 10 spaces, each side of fracture.

Section.		Edges. mean	Side.	$x - y$	$\frac{x+y}{2}$	Marks.
$a \times b$ in.	a/b	x%	y%	%	%	
.273 × .82	⅓	—	—	—	—	*D* 21
		46.0	46.5	− 0.5	46.3	*D* 22
		49.2	48.5	+ 0.7	48.9	*D* 23
		50.8	50.1	+ 0.7	50.5	*E* 21
		49.6	48.9	+ 0.8	49.3	*E* 22
		45.6	45.4	+ 0.2	45.5	*E* 23
		35.3	35.1	+ 0.2	35.2	*F* 21
		28.6	27.7	+ 0.9	28.2	*F* 22
		23.3	22.9	+ 0.4	23.1	*F* 23

The error due to measurements on the face, as compared with that on edge, amounts to 0.8%; the determination as a mean of the edge-measurements, compared with the average of the three, varies as much as 0.4%.

In Table 12 I have tabulated the averages of variations $x - y$ obtained from identical bars of copper having the dimensions of cross-section as stated in the first column, the

elongation in one case having been obtained from a length $l_g = 5l_d$, and again $l_g = 10l_d$.

Table 12. Differences of Elongations, determined on Both Edges (x) and on One Face (y) of Copper Bars.

(Abstract of *L 110*, pp. 92–97. Table 22.)

Elongations in tenths per cents.

Sheet Metal. Form of Bar.	*A*		*B*		*C*		*D*		*E*		*F*	
	δ_5	δ_{10}	δ_5	δ_{10}	δ_5	δ_{10}	δ_5	δ_{10}	δ_5	δ_{10}	δ_5	δ_{10}
.39 × 1.17 in. *a*	9	−1	7	12	9	3	—	—	—	—	—	—
.273 × .82 " *b*	8	5	7	31	5	0	16	12	4	3	11	6
.273 × .273 " *c*	—	—	—	—	—	—	0	0	2	1	−3	−1
.273 × 1.365 " *d*	—	—	—	—	—	—	6	4	?	7	5	5
.273 × .273 " *e*	—	—	—	—	—	—	22	9	13	9	8	2

Tables 11 and 12 show that measurements on the two edges invariably give greater values than those on the faces, and Table 12 shows that these differences are greater with shorter gauge-lengths than when the latter are longer. The averages of five tests already show that the differences in case of very wide test-pieces may amount to 2 units of $e\%$; in individual cases it is of course greater. In bars having ratio of thickness to width of 1 : 3, variations of more than 1% are obtained; the smallest differences are found when this ratio is 1 : 1 (square section), and the greatest when it is 1 : 10. I have demonstrated this in still greater detail in my report on investigation of copper (*L 110*, p. 81 *et seq.*).

As will be seen from these results, unilateral measurements of extension on face of test-pieces of cross-sectional ratio 1 : 4, having a gauge-length of sufficient size (which is again to be referred to later on), are only permissible when casual errors of elongation of 1% are allowable. This error is of course only noticeable in material which contracts very considerably. Measurements must of course be made on a central scribe-line, beginning at the

edges of fracture (*131*). I must not fail to call attention to the fact that the inspector of the material certainly does not treat the producer poorly when he allows elongations of flat bars to be determined from averages of measurements of extension of the faces.

138. Remembering the discussion (*135*) of the effect of grips or shoulders, doubts may certainly be expressed as to whether it would not be more accurate theoretically to determine elongation by doubling the measurements on the long end of the fracture, instead of supplementing the single measurement, including the entire fracture and contraction of the short end as previously described, because the deformation at the contracted section on the long end is least affected by the influence of the shoulders. But the fracture does not always coincide with one of the divisions, and hence a certain correction would become necessary, to be strictly accurate. When the fracture is decidedly funnel-shaped, the narrowed part a, Fig. 99, "gorge," at which the maximum elongation is found, does not coincide with the fracture $a_{,,}$ and it may in fact be located at a considerable distance beyond the bottom of funnel, hence raising doubts as to which point is to be used as the origin of measurements when using this method. When using the method adopted by public laboratories, of supplementing the missing spaces of the short end, this doubt is avoided.

139. Many tests have been made to determine the magnitude of errors of determination of elongation when measuring extension between two gauge-marks, as compared with the true elongation. Observations made on a single test-bar by measuring the proportional spaces will easily convince any one that the errors may amount to several units of elongation. Table 13, A, gives values of elongation of the same material as averages of several series of measurements. Fracture is always found at division 18. The elongations have been determined from the several series of figures and under the various assump-

tions, as though rupture had occurred at $\frac{1}{4}$, $\frac{1}{8}$ or $\frac{1}{2}$ of the gauge-length. Grouping these values of elongation as in B, Table 13, and again reducing them on the basis of making the value obtained as if the fracture had occurred as at $\frac{1}{2}l = 100$, will give the relative values as arranged in the second part of B, Table 13.

140. These values apply to low steels (Flusseisen), in general use in structural work. *The great effect of location of fracture within the gauge-marks* on values of elongation $e\%$ will be self-evident. When rupture occurs in the middle third of the length, errors up to 4% of the value of $e\%$ are still possible. In order to at least exclude the maximum error it is advisable

> *to use the method of direct measurement of extension between gauge-marks only in such cases where rupture takes place in the middle third of the gauge-length.*

This rule is of course only absolutely necessary in material which shows large contraction, in which therefore elongations of the several parts of the bars are materially different. But it must be emphasized at this place that the *scientific value of statements of elongation of strongly contractile material is a very doubtful one when the method of deriving it is not stated at the same time.* This fact should be emphasized on every appropriate occasion, because the conviction of its far-reaching importance is as yet by no means common property.

a. There is, however, another reason which justifies the rule above laid down, that direct measurement of extension is permissible only on bars having the point of rupture located in the middle third. It is the fact, already repeatedly mentioned, that the previous supposition of symmetry of deformation about the point of rupture, in case this is located near one end of the bar, frequently no longer holds good (*135*,

Fig. 92). It may be surmised that the still remaining residuary error may even be smaller under certain conditions, after the exclusion of bars ruptured beyond the middle third, as proposed in Sect. 140, than that committed by the testing laboratories with their complex method, and still existing in case of rupture occurring near one end, because of the effect of shoulders. However, very exhaustive investigations of this matter must still be made. At any rate, this consideration was the cause which led me to propose the adoption of the method described in Sect. 140 to the Association of German Ironmasters.

b. I must here discuss another proposition made in many quarters, and which was advocated, among many others, by v. Tetmajer. It is a common opinion that the deformation adjoining point of rupture, the actual stricture, should be excluded, because extensibility of a bar may be considered as due to two parts, namely that due to stricture, which shows the extensibility of but a very limited part of the bar, and of a second due to a uniform behavior of the entire length of bar. The latter alone was proposed to be used as a measure of quality of the material. However, the assumption that elongation is constant during any period of the test over the entire length l_e of bar is approximated only in case l is assumed to be very great. In our short test-pieces, however, the effect of grips becomes noticeable even within the elastic limit, and it is strikingly manifest, as has been frequently stated, under the condition of bar which alone is here to be considered, that after rupture. In a bar of limited length there is in fact no part in which the extensibility is constant over a great length. Should this have been determined from test, it would be either merely accidental or due to method of applying values which is not free from criticism. When, however, the principal assumption of the proposition here discussed is inaccurate, the

degree of error of the proposed method, its novelty and advantage for determining qualities of material are very questionable.

b. Influence of Gauge-length l_g.

141. When extensions of a bar provided with spacing are measured as is done in public testing laboratories (*136*) and on different lengths, i.e., on different numbers of spaces symmetrical with relation to point of rupture, values essentially different will be obtained from bars showing great contraction, as becomes instantly self-evident from an examination of diagrams of elongation, as in Fig. 89, and a comparison of values under B, Table 13. Comparing these final

Table 18. Influence of Location of Fracture and Gauge-length l_g on the Determination of Extensibility.

Spacing	A. Elongation of each Division in Per Cent. Test Series.				
	a	*b*	*c*	*d*	*e*
1	17.4	17.1	14.5	—	—
2	19.1	19.2	14.5	—	—
3	20.4	21.9	14.5	—	—
4	21.2	22.5	15.5	15.5	13.0
5	20.4	23.7	15.0	16.0	16.0
6	21.4	23.4	16.0	16.0	17.5
7	22.3	23.7	16.0	18.0	19.0
8	21.5	25.1	16.5	20.0	19.0
9	22.4	25.1	18.0	20.5	20.0
10	21.7	25.5	20.0	20.5	22.0
11	23.7	23.3	19.5	21.0	22.5
12	22.2	23.5	20.0	21.5	23.0
13	24.0	25.1	20.0	22.5	22.3
14	25.1	26.4	22.1	22.0	25.0
15	26.6	29.9	22.8	26.0	28.8
16	30.5	38.2	27.0	32.5	34.3
17	50.1	72.9	56.5	44.5	58.0
Rupture	95.8	86.0	97.3	78.0	128.5
19	39.3	43.8	56.0	60.8	81.8
20	32.0	32.0	27.0	38.3	41.5
21	27.5	27.8	22.2	29.5	30.3
22	29.1	26.7	22.2	26.5	26.0
23	27.6	25.5	21.5	23.8	25.3
24	25.8	24.4	23.8	22.5	24.5
25	26.1	24.7	23.0	22.5	25.0
26	25.8	25.5	22.8	21.3	24.8
27	23.3	25.1	20.2	21.3	24.5
28	23.0	25.1	18.5	20.5	24.8
29	22.3	24.7	20.0	20.0	24.5
30	22.4	23.4	20.0	19.0	24.5
31	20.8	23.7	20.0	17.0	23.3
32	19.8	22.5	19.0	16.5	23.0
33	19.6	21.9	19.5	16.5	25.5

Test Series	B. Elongation referred to gauge-length l_g and location of fracture.								
	$l_g = 20\, l_d$				$l_g = 10\, l_d$			$l_g = 5\, l_d$	
	at end	at $\frac{1}{4} l_g$	at $\frac{1}{3} l_g$	at $\frac{1}{2} l_g$	at end	at $\frac{1}{3} l_g$	at $\frac{1}{2} l_g$	at end	at $\frac{1}{2} l_g$
	or in spaces								
	1 20	4 23	5 24	9 28	9 18	12 21	14 23	14 18	16 20
a	28.9	30.2	30.5	31.1	34.2	37.3	38.4	45.6	49.5
b	31.5	32.6	32.7	33.4	38.6	40.6	42.0	52.7	54.6
c	26.4	27.6	21.0	29.0	32.3	37.1	37.5	45.1	52.8
d	—	28.7	29.0	29.9	30.9	31.6	38.2	40.6	50.8
e	—	33.7	34.2	35.4	38.5	47.4	48.0	54.9	68.6
	or in proportion to rupture at $\frac{1}{2} l_g$								
a	93.0	97.0	98.3	100	88.8	97.1	100	92.2	100
b	94.4	97.7	98.0	100	91.9	96.7	100	97.0	100
c	91.0	95.2	96.5	100	86.2	98.8	100	85.2	100
d	—	95.9	97.0	100	81.0	98.5	100	80.1	100
e	—	95.0	96.3	100	80.2	98.7	100	79.8	100
Mean	92.8	96.2	97.2	100	85.6	97.6	100	88.5	100

Series of different kinds of low steel (Flusseisen):
a. Mean of round bars.
b. " " flat bars.
c. " " round bars.
d. " " flat bars.
e. " " flat bars.

values on the assumption that the values found for $l_t = 20 l_d$ are equal 100, we shall obtain the following comparison, Table 14:

Table 14. **Influence of Gauge-lengths on Values of Elongation.**

Elongation in % of l_g, referred to fracture at centre.

$l_d = 20$; $l_d = 10$; $l_d = 5$ corresponds to proportion $n = \frac{l_g}{\sqrt{a}} = 11.3$; 8.5 and 3.5 (*159*).

Shape. Low steel (Flusseisen).	$l_d \cdot 20$ %	$l_d \cdot 10$ %	$l_d \cdot 5$ %	Or referred to $l_d \cdot 20 = 100$	
				$l_d \cdot 10$	$l_d \cdot 5$
a. Mean of rounds*.....	31.1	38.4	49.5	123.5	159.2
b. Mean of flats*........	33.4	42.0	54.6	125.7	163.7
c. " " rounds*.....	29.0	37.5	52.8	129.2	182.0
d. " " flats†........	29.9	38.2	50.8	127.2	169.7
e. " " " †........	35.4	48.0	68.6	135.5	193.7

* Personal tests. † Bauschinger's tests (Mittheilg. Munich XXI. p. 22).

142. The discussion of the previous propositions has already developed that total extension may be considered as composed of the sum of the extension of the bar before beginning of local contraction, and the extension of the contracted part. As soon as the bar is very long, i.e., as soon as the effect of shoulders and grips may be neglected, it may be assumed that that part of the bar beyond the part of local contraction almost retains its prismatic shape during contraction, i.e., undergoes a uniform extension in all parts. If β be the extension of the unit length up to the moment of local contraction, then

$$e = \beta . l_g, \quad \text{up to that instant;}$$

or in % of gauge length:

$$e\% = \frac{\beta l_g}{l_g} . 100 = \beta . 100,$$

β being a constant for any given material.

If extension now takes place during local contraction e_c, then

$$e = \beta l_g + e_c,$$

or in per cent of l_g:

$$e\% = 100\left(\beta + \frac{e_c}{l_g}\right). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad 10$$

A term independent of the gauge-length is added.

143. Because of the effect of grips, which was omitted in the construction of this formula, it cannot be strictly accurate for every length l_g. This effect of grips is, however, less noticeable as the length increases. In short bars, as used in testing materials, to avoid unnecessary expense of testing, the so-called proportional elongation no longer appears distinctly separated from the local extensibility near the gorge. The merging of one into the other disappears more completely as shorter bars are used.

144. As the effect of length of test-piece on determination of elongation is dependent on local contraction, it becomes clear that hard and soft, i.e., slightly and highly ductile, materials must show an appreciable difference. In less ductile materials the effect of length on the results of measurements is naturally less than in those more highly ductile, and generally more contractile. As long as wrought iron with its low ductility and slight contraction was the principal material for constructions, the influence of length of test-piece on results of measurements was hardly noticed in routine work. As the use of low steel (Flusseisen), a highly ductile material with large contraction, increases, it will become more and more obligatory to carefully study this influence, and to adopt rules which will eliminate it.

c. Influence of Size of Section.

145. Under the assumption of a homogeneous material it may certainly be expected that it will always suffer similar deformations under like circumstances (*L 100, 102, 118, 123, 129, 130*), at least there is no forcible reason to expect any other result; experience has demonstrated this "law of similarities," as was probably first verified by Lebasteur and Marié, 1878 (*L 102*, Vol. I, p. 120), for circular sections, and for rectangular sections by Barba in 1880, and was shown to apply between wide limits, as will be more fully shown below.

Under the assumption of similar sections and long bars there is no reason to imagine that dimension of cross-section exerts any influence on uniform extension βl_r or of uniform elongation 100β of test-bars.

146. It may be expected that local extensibility is proportional to cross-sectional dimensions, hence proportional to cross-sectional area, for similar shape and identical material. This assumption has been verified by many tests (*L 2*, Part 6 and 21–131).

We may assume with Bauschinger:

$$\lambda_e = \gamma \sqrt{a},$$

in which γ is a constant peculiar to the material, due to the above assumption:

$$e\%_e = 100\frac{\lambda_e}{l_r} = 100\gamma\frac{\sqrt{a}}{l_r};$$

hence

$$e\% = 100\left(\beta + \gamma\frac{\sqrt{a}}{l_r}\right). \quad . \quad . \quad . \quad . \quad 11$$

And for a second bar of the same material but of different section:

$$e\%_1 = 100\left(\beta + \gamma\frac{\sqrt{a_1}}{l_{g_1}}\right);$$

and when $e\%$ is to be equal in the two cases, then $e\%$ must be $= e\%_1$, or

$$100\left(\beta + \gamma\frac{\sqrt{a}}{l_g}\right) = 100\left(\beta + \gamma\frac{\sqrt{a_1}}{l_{g_1}}\right),$$

or $$\frac{\sqrt{a}}{l_g} = \frac{\sqrt{a_1}}{l_{g_1}}, \quad \text{hence} \quad l_g : l_{g_1} = \sqrt{a} : \sqrt{a_1}, \quad . \quad 12$$

and therefore: gauge-lengths must vary as the square roots of sectional areas, when similar bars of identical material, having different sectional areas, should show identical elongation.

This proposition is self-evidently only aplicable to bars having considerable length. For bars of short length the effect of grips must again be considered.

d. Influence of Shape of Section.

147. From general considerations based on assumptions having a high degree of probability, but verified by many tests, it was possible to elucidate the effect due to length and to size of section, assuming such bars in which the influence of grips and shoulders may be neglected. Results of tests alone, however, instruct us as to the effect of shape of section. The previous discussion has demonstrated that we must adhere to the use of comparable bars having lengths l_g proportional to the square roots of the sectional areas. Besides this, we must fulfil the assumptions on which the formulæ derived are based. i.e., bars of greatest possible length, of identical material, are to be selected,

and their elongation $e\%$ determined from the measurement of previously scribed spaces, symmetrically located about the point of rupture.

Hence gauge-lengths must vary as

$$\frac{l_g}{l_{g_1}} = \frac{\sqrt{a}}{\sqrt{a_1}} \quad \text{or} \quad \frac{l_g}{\sqrt{a}} = \frac{l_{g_1}}{\sqrt{a_1}}.$$

148. By plotting Bauschinger's results of tests obtained during his investigation of the laws of the effect of shape of bars (*L* 2, Part 21, Tables I and II), in accordance with the above principle, it will be found that elongations arranged according to the ratio $l_g : \sqrt{a}$ (Fig. 100), in spite of different shapes of cross-sections (circle to rectangle of ratio $w/t = 3$) and of varying dimensions, will conform to a smooth curve with practically sufficient approximation, only a few points deviating to any degree from it.

Bauschinger compared all values of elongation determined with ratio $l_g/\sqrt{a} = 8.5$ in his above-mentioned series of tests, with those obtained from the same material in shape of standard tests-bars of gauge-length of about 6 in. (15 cm) and diam. $= 0.8$ in. (2 cm) and the use of ratio $l_g/\sqrt{a} = 8.5$. When the values of $e\%$ thus found are plotted according to increasing section as in Fig. 101, it will be recognized that cross-sectional area exerts but a slight effect on the value of elongation, within the limits investigated and with the material used. Possibly a very slight decrease of elongation $e\%$ under increasing section may be deduced from Fig. 101.

149. By calculating averages from results of bars of equal ratio w/t and tabulating them according to increasing values of w/t (width to thickness) the following Table 15 may be

deduced from Bauschinger's Tables I and II for bars of ratio $l_g/\sqrt{a} = n = 8.5$.

Table 15. **Influence of Shape of Section on Elongation.**
Elongations $e\%$ determined for $l_g/\sqrt{a} = 8.5$

Bauschinger's Mittheilungen, Part 21.

	Table I.		Table II.	
	Elongation $e\%$	Number of Tests	Elongation $e\%$	Number of Tests
Rounds.	32.9	7		
Flat bars $\frac{w}{t}$				
1.3	—		33.2	2
1.4	31.0	1	—	—
1.5	—	—	33.3	1
1.7	31.7	4	33.5	5
1.8	33.0	1	—	—
2.1	31.8	2	33.2	1
2.5	(29.9)	1	—	—
3.0	32.0	1	34.5	1

These figures show that shape of section within the limits of the tests has not had any noticeable effect. Although the shapes used in routine work are included within the limits of those used by Bauschinger, it is nevertheless necessary to collect additional results of tests, and especially to extend the investigation based on similar points of view to other materials.

150. The similar earlier tests by Barba (*L 118* and *119*) were made on a somewhat different plan and do not permit such a general comparative review as previously given. Their study is, however, valuable and to be strongly urged. Fig. 102 is here referred to, which represents elongations plotted as in Fig. 101, deduced by Barba, from low-steel (Flusseisen) bars of different section, having lengths proportional to sectional area. In addition to these another of his investigations may be discussed, because he shows the effect of grips and shoulders on value of $e\%$ in a very instructive manner.

Barba tested a series of bars of equal diameter of one material, low steel (Flusseisen), but of different end lengths, having identical shoulders, and compared the values of $e\%$ thus found (line A, Fig. 103) with those of $e\%$ (line B) determined on various gauge-lengths selected on a bar of great end-length, initially provided with spacing, and of a diameter the same as that of bars of series A.

Hence, according to Fig. 103, elongation was considerably affected in Barba's tests by the action of the shoulders, but less as the length of bar increased. The importance of the limitations regarding the formulæ of the effect of length and section on the results of determinations of elongation will become apparent. It is also clear that comparisons cannot as yet be made between elongations of short gauge-lengths of long bars and those determined on the same gauge-lengths on short bars, even when the values of $l_g / \sqrt{a}$, as well as the sectional area and shape, are identical; for when using standard bars of 0.8 in. (2 cm) diam. and $l_g = 8$ in. (20cm), hence $\frac{l_g}{\sqrt{a}} = 11.3$, Barba obtained $e\% = 34.5\%$ in case of the long bar and also $e\% = 28.3\%$, hence a difference of 100 : 82. This is an apparent contradiction of the Bauschinger results given in Sects. 148 and 149, which proved that elongations $e\%$ were found to be the same when $l / \sqrt{a}$ was the same, even when sectional area and shape were different. Hence it will be readily seen that such additional directions for methods of testing must necessarily be adopted which eliminate the effect of shoulders, when it is desired to obtain identical elongation with bars of different dimensions, as would be obtained from a standard bar of identical material of 0.8 in. (2 cm) diam. and 8 in. (20 cm) gauge-length. It comes natural to examine the

results of tests as to whether they satisfy formula 11 stated in (*146*):

$$e\% = 100\left(\beta + \gamma\sqrt{\frac{a}{l_t}}\right).$$

This has been attempted in Fig. 104 with the results of Barba and Bauschinger previously given, and others by Martens; the tests refer to bars of very various shapes and sectional area of low steel (Flusseisen) of different tenacities, and of several kinds of copper. It will be seen that as a whole the diagrams approximate right lines. This proves the general correctness of the assumption of indifference of sectional shape, within practical limits. Nevertheless the lines *c* show discrepancies which are not readily explained. Lines *h* are also striking. They represent the two curves, Fig. 103, found by Barba; *h'* represents elongations determined from individual spacing on the long bar [20 in. (50 cm) between shoulders], and *h* the elongations as determined on identical gauge-lengths of short bars; the influence of shoulders must have become more pronounced in case of short bars.

e. The Law of Similarity.

151. When discussing the effect of stricture on the value of $e\%$, use was made of the consideration that deformations of long bars of quite homogeneous material would of necessity be similar, provided the shape of section was similar. It was seen that dimensions and shape of section, within the limits used by Bauschinger, i.e., those which cover general practice in testing materials, had no material effect on elongation, as long as the gauge-length was made proportional to the square root of the sectional area. Bauschinger, however, mainly used bars in which the finished or end length (length between shoulders) exceeded the

gauge-length but slightly, and on which the heads (shoulders) were approximately similar.

The law of similarity, as Barba called it (*L 118* and *119*), or the law of proportional resistances, as Kick (*L 100*) named it from a broader point of view, can be formulated for the case in hand as follows:

"Under identical conditions and stress, bodies of identical material and of geometrically similar shape undergo geometrically similar deformations."

Hence it is to be expected that equal elongations will be obtained from two test-pieces, within the unavoidable differences of material and limits of errors of testing, when all dimensions, those of the shoulders, necks, fillets, finished length, gauge-length and spacing within the latter, were made proportional to each other. Strictly speaking, all secondary conditions must also conform to this law of similarity; gripping must, for instance, be similar, etc. These matters sometimes make it difficult to determine the cause of variations from the law when results occasionally contradict it.

152. A general derivation and demonstration of the law by results of tests would lead us too far; it will probably suffice to mention the work of Barba (*L 118*, *129*), Bauschinger (*L 2*), and Kick (*L 100*), which, all of them, refer to the literature on the subject, and partly discuss it.

For the purposes of this book it will suffice to bring proof by means of Fig. 105 as to the high degree of agreement of elongations, even in individual spaces on bars, when measurements are made on geometrically similar lengths of geometrically similar bars. The curves represent extensions of every individual space on the bars up to the fracture, in % of l_d; full lines refer to rough rolled bars and to flat bars having the roll-scale on their faces; the

dotted lines refer to bars finished all over. The material is low steel (Flusseisen). The full lines (large sections) and dotted lines (small sections) cover each other as closely as can ever be expected to occur in such tests. Group *D*, Fig. 105, which gives curves of averages of the curves *A* (rounds) and *B* and *C* (flats) without regard to dimensions of bars, gauge-length varying from 0.56 to 0.43 $\sqrt{a}$, clearly shows that shape and area of section are without influence.

I have discussed the matters referred to in the previous sections very exhaustively in my report of tests of copper (*L 110*, p. 98 *et seq.*), giving many examples, and especially emphasizing that, if the law of similarity be strictly fulfilled, the diagrams for S and e for different bars, but geometrically similar,* must coincide at all points. Discrepancies were proven to exist in the case of soft copper, which have not yet been explained; with hard copper, the requirements were fulfilled almost completely.

8. Influence of Shape of Bars on Stress S_P, S_Y, S_M, and on Contraction c.

153. After having learned what important influence the shape of test-piece exerts on the values of elongation of a material, it remains to investigate whether stress at proportional limit S_P, yield-point S_Y, and at maximum stress S_M, as well as contraction c, are subject to a similar effect.

Again referring to results of Bauschinger's tests (*L 2*, Part 21) of low steel (Flusseisen) and wrough-iron round and flat bars of different sectional area, and plotting them according to magnitude of area, the comparison shown by Fig. 106 will be obtained.

* According to elucidations in Chapters γ and δ, this holds true in general for bars in which equal conditions $l_g = n\sqrt{a}$ obtain and the influence of shoulders is made to act in an approximately similar manner.

The ratio of cross-sectional dimensions of flat bars $w:t$ varied from 1.3 to 3.0. All values of $e\%$ are those of gauge-lengths $l_g = 8.5\sqrt{a}$, and must therefore, according to the previous chapter c, be equal in both groups, as long as the finished or end lengths are chosen with a definite relation to $l_e\sqrt{a}$, and the shapes of shoulders were similar, which, however, was not strictly true in Bauschinger's bars. The finished or end length varied between $l_g\sqrt{a} = 8$ to 17, and was in fact 24.7 in one case.

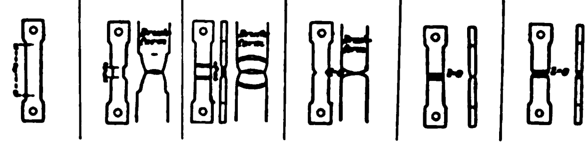
From both groups in Fig. 106 it is apparent, what has moreover been amply confirmed in regard to stress by numerous tests of early and recent authors, that the influence of section and of shape of bar, within the practical limits of dimensions and within the limits of $l_g = (8 \text{ to } 17)\sqrt{a}$ for all points observed, i.e., stress at E, at P, at Y, and at M, as well as of deformations c and $e\%$, is very slight, as long as $e\%$ is determined from lengths which are proportional in all bars to $\sqrt{a}$. (N.B. It must, however, not be forgotten that these deductions must be referred only to those materials from which they were obtained.)

154. Even when the results of Bauschinger's tests are arranged according to differences of values of $l_g\sqrt{a}$, we will reach the result that influence of shape and magnitude of cross-section, as well as the ratio of finished or end length to sectional area, has practically no influence, within the limits investigated by him, on the stress E, S_P, S_Y, and S_M. On the other hand, this comparison shows that $e\%$ and c (i.e., deformation) are slightly affected, as they increase slightly when the ratio $l:\sqrt{a}$ increases, which would again confirm the law previously stated about the effect of shoulders and grips, because it is asserted that elongations $e\%$ observed on proportional gauge-lengths $(l_g = 8.5\sqrt{a})$ increase as the proportion $l:l_g$ increases.

If it is desired to clearly trace the effect of shoulders by tests, it will be necessary to vary their shapes to an ex-

aggerated degree; but few tests of this kind have as yet been made. Some ideas in this direction may be obtained from Table 16, in which I have tabulated the results of Barba's tests.

Table 16. Results of Barba's Tests on Influence of Shape (Flusseisen).



	a	*b*	*c*	*d*	*e*	*f*
Dimensions.*						
Width w	1.20	0.55	1.20	0.55	1.20	0.55
Thickness t	0.55	0.55	0.23	0.55	0.23	0.23
Sectional area a	0.66	0.30	0.276	0.30	0.276	0.126
Gauge-length l_g	8	4	4	0	0	0
$l_g/\sqrt{a}$	9.8	0.7	0.7	0	0	0
Results of Tests.*						
S_M	59700	61900	62600	65000	81200	86000
$e\%_{l_g}$	30.5	65.0	40.0	45.7	57.1	60.4
c	61.8	51.3	49.8	very slight	almost 0	0

* Dimension and stress reduced from metric system are approximate values.

It will be seen that the contraction c becomes less as the effect of shoulders is allowed to become more pronounced; if it is prevented altogether, as in forms d, e, and f, in which l_g is almost equal to 0, elongation $e\%$ will also become immeasurable, whether immeasurably great or immeasurably small cannot be instantly decided. From the foregoing it was learned that elongation increases with decreasing gauge-length; it is questionable whether this law is valid without limitations. It might be possible to deduce a limitation from the equally valid law of effect of shoulders, which act to decrease elongation. The less a bar is allowed to fulfil the tendency to contract because of the effect of shoulders, the greater will be the apparent tenacity. Hence the fact deduced from Bauschinger's tests, that stresses at E

P, Y, and M are unaffected by cross-section, will most likely be correct only between limited values.

In Section 103*d* I previously referred to similar tests made at Charlottenburg (*L 132*). In these tests of bars with circumferential grooves or screw-threads an increase of tenacity, up to 19%, could be demonstrated.

9. On Shapes to be used in Tension-tests.

155. The recognition of the fact, repeatedly mentioned in the foregoing sections, that the shape of test-piece is not without influence on the results of the tension-test, led to the adoption of standard shapes in the art of testing materials, soon after its general introduction. These shapes were originally used in small districts, and sprang up in many places; they were hence manifold, and therefore unobjectionable comparison of results of tests obtained at different places was not possible. Railway managers, great technical governmental departments, the large technical associations representing the interests of producers and consumers, constantly sought to harmonize larger circles, urging the adoption of the propositions made by them. Finally, the Conferences for Unification of Methods of Testing Materials, previously frequently mentioned, were convened in Germany, as well as similar conventions in other countries, which attempted to unify conditions in each country and if possible internationally. Nearly all engineering associations in many countries have taken the liveliest interest in these questions, which has recently led to the formation of a large International Association for Testing Materials, which has a membership, rapidly growing, of over 1600 members, representing more than 25 countries. The association is attempting the unification and improvement of the entire science of testing materials.

156. As has been repeatedly stated, the round rod of

0.8 in. diam. and 8 in. length (2 cm and 20 cm) is at present in most general use. This bar has even in Germany generally displaced the 1-in. bar (2.5 cm), because the larger bar requires more powerful testing-machines, which becomes objectionable because of the more general use of the stronger low steels (Flusseisen).

a. At present I shall not discuss all proposed so-called standard shapes of test-bars, because this would lead us too far, but, using the deductions developed in the foregoing sections, shall confine myself to those shapes which have been adopted by the Royal mechanical technical Testing Laboratory at Charlottenburg which is under my direction (*L 133*). The standard round bar was adopted as a basis, and flat bars of equal section and of ratio $w:t$ not exceeding 5 were adopted. When for any reason the test-bars must have a section greater or less than 0.487 sq. in. (3.14 sq. cm), then all other dimensions are made as in the case of the round bar in relation to $\sqrt{a}$ as a unit. Bars of section 0.487 sq. in. and of $w:t = 1$ to 5 are called "standard bars," those of different section a, but proportional dimensions, are called "proportional bars," in accordance with Bauschinger's method. These proportional bars, however, are not given indefinite areas, but these increase in such manner that spacing l_d also increased proportionately varies by whole units of 0.04 in. (0.1 cm).

b. It is necessary to use a whole set of corresponding spacing-gauges (Fig. 95) for laying off these spaces, and proportional scales, divided acording to per cents of l_d, are used for determining elongation, so that e and $e\%$ can be read off directly for any length l_r. Similar provision has been made for measurements of precision, the scales also being divided in proportion to the length l_e used for this purpose. Hence all readings are made as referred to the length of observation, and all that is necessary is to arrange the testing-machines so that stress can be read off directly, instead of loads, with ample practical accuracy, or that diagrams of S and e can be

plotted. I shall show later on that this is possible. The great value of such arrangements will be readily appreciated when it is considered that an extraordinarily complete and rapid survey of the material tested can be thus obtained, with great simplification of calculation, for identical materials must show equal elongations $e\%$ under equal stress S during all periods of test when using comparable shapes of test-pieces, and diagrams plotted according to S and $e\%$ must coincide.

157. If it is desired that bars varying in section from the standard round rod give practically the same result as obtained from the latter, they must have sections and dimensions which have been chosen in accord with the law of similarity and the experience that shape of section is without influence.

The standard round bar used at the Charlottenburg Testing Laboratory has dimensions as shown by Fig. 107 on left half of bars. Proportional bars, based on the former, are given dimensions based on $\sqrt{a}$ as unity, as shown on the right-hand halves of bars shown in Fig. 107; it is also to be remarked that the dimensions of shoulders are based upon the width w of the section of body of bar, and that the fillet at the shoulder is said to have a radius equal to one half the diameter of the mill used in forming it. The diameter of mill is assumed as .273 in. (7 mm), but it may vary from 0.234 (6 mm) to 0.312 in. (8 mm).

158. When prismatic (rounds and flats) bars without shoulders are to be tested, the length L between grips should be appropriately $= 20\sqrt{a}$, and using a gauge-length $l_t = 11.3\sqrt{a}$, and the spacing $l_d = 0.565\sqrt{a}$, as in the proportional round bar.

a. The foundation of the system above described might undoubtedly be greatly simplified if the selection of test-pieces could

be entirely systematic, and if we were not bound to a certain degree by a very general custom and common usage. It would moreover be especially beneficial to adjust the selection of sectional areas of standard bars to the metric system, by adopting the areas as 2, 2.5 and 5 sq. cm (0.31, 0.377 and 0.775 sq. in.) to facilitate the mental arithmetic of transforming loads into stress, or avoiding it entirely by the application of proper relative designations on the poise-weights. Unfortunately, however, 0.31 sq. in. (2 sq. cm) is rather small; 0.775 sq. in. (5 sq. cm) requires larger machines; while 0.377 sq. in (2.5 sq. cm) sections produce inconvenient conditions of poise-weights.

b. The shapes of test-pieces above described appear very manifold at first sight, and practically difficult to use. The matter is, however, by no means as difficult as it appears. The individual dimensions of standard bars, as well as of the proportional bars, made on the basis of $\sqrt{a}$ as a unit, are tabulated, and gauges are made for the principal dimensions. These tables and gauges are few in number, as bars of indefinite sections are not used for proportional bars, which are limited to a few graduated types. These several graduated shapes are marked with definite numbers which are also placed on the gauges, spacing-gauges, and the percentile gauge for elongation, so that manipulation and preparation of test-bars are not inconvenient after having become familiar with the system.

c. Account must always be taken of the fact that bars will never be finished accurately to directions; section must hence invariably be determined by actual measurement. In order to abbreviate calculations a series of printed tables have been published (*L 206–208*), which make it possible to read off stress directly, for any area or load. If approximations are sufficient, the ordinary slide-rule will suffice for calculation; it must be remembered that an accuracy of ± 1% will suffice for most practical purposes.

159. It will be clearly seen from the foregoing paragraphs that the true value of results of tension-tests can be alone recognized, and that reports, especially of elongation after rupture, deserve scientific recognition only in case they permit understanding the method and conditions under which the results had been obtained. The rules proposed in the previous section would also necessarily appear valueless and exaggeratedly painstaking if the value of elongation were given or published without a statement of the gauge-length used. For this reason I made the proposition in my report of investigations of copper (*L 110*, p. 107):

that the factor of elongation $n = l_g/\sqrt{a}$ be appended as an index to the value $e\%$ of the elongation after rupture, hence writing it: $e\%_n = x$.

Hence $e\%_{11.3} = x$ would be the form for the standard bar.

Although I have repeatedly indicated that all explanations in secs. 1 to 9 (*L 110*) relate essentially to circumstances obtaining in tension-tests of metal bars, I nevertheless desire to again emphasize it in this place, so as not to mislead in any manner. For other materials and under other circumstances it will become necessary to reflect or to make independent investigations to determine to what extent the views previously given may apply.

Other considerations are determinant in other cases, e.g., of wood, leather, silk, and paper (bodies of density $d < 1$). Stone, cement, concrete, etc., must be tested under tension in shapes other than those used for metal; textile fabrics, thread, fibre or glue, solders, etc., require special procedure, and the results are affected by factors other than those which could be considered in the foregoing chapters.

It would lead us too far if I were to take up all of these points in this place. I make the reservation to revert to the most important matters when discussing the properties of materials later on.

10. Influence of Shape of Test-piece on $-S_Y$, $-S_M$ and on $-e\%$.

160. The law of similarity also applies to crushing-stress. It can be enunciated as follows:

Bodies of identical material and of geometrically similar shape undergo geometrically similar deformations under identical conditions and stress.

From this we may make the particular deduction that equal crushing $-e\%$, referred to original height, will be obtained from tests of cubes of identical material having dif-

ferent dimensions, when subjected to equal crushing-stress — S. The crushing* at rupture — $e\%$ must also be the same regardless of the dimensions of cube used.

The law of similarity can, however, apply rigidly only to those bodies which have a perfectly homogeneous structure; i.e., whose structural conditions are geometrically similar. It can, for instance, be applied to wood only when the conditions of growth conform to the law of similarity in the test-pieces compared. This consideration was the reason which led me to propose the selection of cubes of wood for comparative tests, cut from disks at different heights, one edge of which touched the bark, while the other coincided with the centre of the heart of the tree-trunk, for use in the investigations made by the Charlottenburg Laboratory, jointly with the Eberswalde Academy of Forestry, of the properties of resistance of Prussian Timber. This, however, did not permit strict compliance with the law, but greatest possible approximation was reached; the necessary use of greatly varying dimensions of cubes was, however, unavoidable.

161. As a matter of fact the tests of Gauthey, Soufflot, Perronet (1774), Rondelet, Vicat (previous to 1833), Bauschinger, and others, (*L 2*, Part 6—*L 134*) prove the correctness of the law of similarity in regard to stress. Table 17 gives some of the results of these tests; further corroboration is to be found in the reports of Bauschinger (*L 2*, Part 6), of myself (*L 135*), and of Kick (*L 100*).

162. The French authors quoted had already proved by tests that resistance to crushing is dependent upon shape of cross-section and length of prism. Bauschinger

* As the terms compression, compressibility, etc., are scientifically applied to other qualities and occurrences, I shall use the word "crushing" as a distinct technical term, which means the reverse of extension (elongation).—G. C. Hg.

Table 17. Crushing Resistance of Geometrically Similar Blocks of Wood.

Tests by	No.	Dimensions.						$-S_M$ in at. Averages.		Remarks.
		t	w	l_g	a	$\sqrt{a}$	$\frac{\sqrt{a}}{l_g}$	Single Av.	Mean Av.	
S. Rondelet (previous to 1833)	1 2 3 4	3 4 5 6	3 4 5 6	3 4 5 6	9 16 25 36	3 4 5 6	1 1 1 1	269 266 266 271	268	Stone
	5 6 7 8	3 4 5 6	3 4 5 6	3 4 5 6	9 16 25 36	3 4 5 6	1 1 1 1	117 114 125 123	120	Different stone
	9 10 11 12	3 4 5 6	3 4 5 6	3 4 5 6	9 16 25 36	3 4 5 6	1 1 1 1	55 55 55 56	55	Different stone
Vicat (previous to 1833)	13 14	2 3	2 3	2 3	4 9	2 3	1 1	74.0 73.9	74.0	Gypsum No. 4
	15 16	1.0 1.5	1.0 1.5	1.0 1.5	1.00 2.25	1.0 1.5	1 1	53.1 52.0	52.6	Fine sandstone
	17 18	1 2	1 2	1 2	1 4	1 2	1 1	33.5 33.4	33.5	Air-dried brick-clay
	19 20	1 2	1 2	1 2	1 4	1 2	1 1	18.0 17.0	17.5	Mortar of hydraulic lime and sand
Bauschinger (1872)	21 22 23 24 25 26 27	5.20 6.00 6.70 8.40 8.50 9.95 10.00	5.20 5.85 6.70 8.20 8.50 9.85 9.85	5.05 5.70 6.55 8.50 8.70 9.60 9.70	27.04 35.10 44.89 68.88 72.25 98.01 98.50	5.20 5.93 6.70 8.30 8.50 9.90 9.92	1.03 1.04 1.03 0.98 0.98 1.03 1.02	690 670 680 710 708 680 685	689	Very fine grayish-blue Swiss sandstone
Vicat	28 29	1 2	1 2	2 4	1 4	1 2	0.50 0.50	42.0 41.3	41.7	Gypsum
	30 31	1 2	1 2	0.5 1.0	1 4	1 2	2.00 2.00	46.3 43.1	44.7	Gypsum
Bauschinger	32 33	6.60 9.95	6.50 9.80	4.75 7.00	42.90 97.51	6.55 9.87	1.38 1.41	676 677	677	Very fine grayish-blue Swiss sandstone
Rondelet	34 35	1.75 2.25	— —	— —	2.41 3.98	— —	— —	14.5 14.0	14.3	Gypsum
34–39 spherical bodies (a = meridional section)	36 37	1.78 2.28	— —	— —	2.49 4.08	— —	— —	10.1 9.9	10.0	Air-dried brick-clay
	38 39	1.70 2.50	— —	— —	2.27 4.91	— —	— —	6.02 5.66	5.84	Chalk and sand
40–43 truncated pyramids.	40	1.00	—	—	0.44 1.00	—	—	45.5 20.0	46.2	Chalk $t : t_1 : l_g$ for 40 and 41 = 1 : 0.66 : 1.6
	41	1.50	—	—	1.00 2.25	—	—	46.8 20.8	20.4	
	42	2.00	—	—	1.00 4.00			84.5 21.1	83.0	Gypsum No. 4 for 42 and 43 = 1 : 0.5 : 1.5
	43	3.00	—	—	2.25 9.00			81.4 20.3	20.7	

deduced the relation between crushing-resistance, $-S_M$ and length of test-piece, l, and section, a, of prism of similar section from the work of these investigators and his own (*L 2*, Part 6) as follows:

$$-S_M = \alpha + \beta\sqrt{a}/l, \quad . \quad . \quad . \quad . \quad . \quad . \quad 13$$

α and β being constants of materials.

163. Bauschinger also deduced the following formula for comparison of prisms of dissimilar sections (*L 2*, Part 6) and ratios of $\sqrt{a}/l_t$ (not less than $\frac{1}{6}$) not too small, from the foregoing tests:

$$-S_M = (\alpha + \beta\sqrt{a}/l_t)\sqrt{\frac{\sqrt{a}}{u/4}},$$

in which u is the perimeter of section. As an approximation for $\sqrt{\frac{\sqrt{a}}{u/4}}$, Bauschinger uses $\sqrt{\frac{a}{u/4}}$. In order to use a shorter expression hereafter the first term shall be written γ, and the approximation γ', the ratio of length $\sqrt{a}/l$, as $\frac{1}{n}$ (compare *149*), and the formula will read

$$-S_M = \left(\alpha + \beta\frac{1}{n}\right)\gamma.$$

The value of γ, dependent upon cross-sectional area, and of γ' will, in cases possibly to be considered in testing materials, be:

for square section	$\gamma = 1.000$;	$\gamma' = 1.000$
" circular section	$= 1.062$	$= 1.128$
" equilateral triangle	$= 0.937$	$= 0.877$

" rectangle of proportion $\frac{t}{w}$, when $t = 1$,

$$= \sqrt{\frac{\sqrt{a}}{u/4}} = \sqrt{\frac{\sqrt{w}}{\frac{2(w+1)}{4}}}, \quad \text{or} \quad \gamma' = \frac{\sqrt{w}}{\frac{1}{2}(w+1)},$$

and hence for the following proportions:

t	1	2	3	4	5	6	7	8	9	10	11	12
γ	1.000	0.971	0.931	0.894	0.863	0.837	0.813	0.793	0.775	0.758	0.744	0.730
γ'	1.000	0.943	0.866	0.800	0.745	0.700	0.662	0.629	0.600	0.575	0.553	0.533

The form of the equation

$$- S_M = \left(\alpha + \beta\frac{1}{n}\right)\gamma,$$

being that of a right line, and proves that the curve of averages of a series of results of observations made on prisms (geometrically similar) of equal section but of different lengths, cut from identical, entirely homogeneous and faultless material, will be a right line, and that each shape of cross-section is represented by a definite line; it will also be noted from Fig. 108 that all of these lines must originate from one point M, provided that Bauschinger's form of formula is strictly correct.

Values obtained from bars of square section and varying lengths would fall on the line marked with a small square; those of circular section on that marked by a circle; and all values of prisms of rectangular section would fall in the space bounded by the line $\frac{t}{w} = \frac{1}{12}$. The values of α and β for square bar would have to be read off directly, and the position of M, according to Fig. 108, would be given by $m = \alpha/\beta$, i.e., by the relation between the two constants of material. The resistance of a cube (i.e., $\sqrt{a}/l_r = 1$) of any size would be given directly by the sum of α and β, the constants.

164. If, however, my remarks given in Section (161) relating to the results of tests collated in my work "On the Influence of Shape of Test-pieces on the Results of Crushing-tests" (*L 135*) be taken into consideration, a quite general confirmation of the fact that crushing-resistance increases with the value $1/n = \sqrt{a}/l_r$ will be found.

From the tables given in the source I collate the following data, Table 18:

Table 18. Crushing-tests of Prisms of Similar Sections and Varying Length, and of Ratio $\frac{1}{n}$.

Comparison of Computed and Observed Values.

Test No.	$\frac{1}{n}$	Section. Shape.	Section. $\frac{l}{w}$	S by Test in at.	S computed. Bauschinger Formula S_1 at.	S computed. From Diagram S_2 at.	Variations. $\frac{S}{S_1}.100$	Variations. $\frac{S}{S_2}.100$	Remarks.
35	0.35	□	1	444	374	437	119	102	Bauschinger; very fine bluish-gray Swiss sandstone; pressure parallel to bed. Bauschinger's average: $-S_M = 262 + 320 \frac{1}{n}$ at. Diagrammatic average: $350 + 249.4 \frac{1}{n}$ at.
36	0.50		1	470	422	474	111	99	
37	0.69		1	557	482	522	115	106	
38	1.02		1	602	588	604	102	100	
39	1.02		1	587	588	604	100	97	
40	1.41		1	677	713	726	95	93	
41	1.38		1	676	704	694	96	97	
42	1.66		1	755	793	764	95	99	
43	1.80		1	659	838	799	78	83	
44	2.12		1	890	935	877	95	102	
45	2.19		1	1145	962	898	119	127	
46	3.36		1	1540	1332	1187	116	130	
51	0.98	□	1	705	648	670	108	105	Bauschinger; identical sandstone, pressure normal to bed. Bauschinger's average: $-S_M = 310 + 346 \frac{1}{n}$ at. Diagrammatic average: $360 + 317 \frac{1}{n}$ at.
52	0.98		1	710	648	670	109	106	
53	1.02		1	685	662	682	104	101	
54	1.03		1	680	665	685	102	99	
55	1.03		1	680	665	685	102	99	
56	1.03		1	690	665	685	104	101	
57	1.04		1	670	669	689	100	97	
58	2.31		1	910	1106	1090	82	83	
59	2.34		1	1130	1110	1100	102	103	
60	2.39		1	1080	1135	1115	95	97	
61	2.98		1	1880	1685	1620	112	116	
62	4.18		1	1750	1750	1680	100	104	
63	4.32		1	1950	1800	1720	108	114	
68	0.25	□	1	381	377	377	101	101	Bauschinger; fine-grained yellow sandstone. Heilbronn in Wuertemberg. Pressure parallel to bed. Bauschinger's average: $-S_M = 347 + 121 \frac{1}{n}$ at. Diagrammatic average: $347 + 119.2 \frac{1}{n}$ at.
69	0.32		1	380	386	385	99	99	
70	0.40		1	395	395	395	100	100	
71	0.47		1	418	404	403	104	104	
72	0.73		1	440	435	434	101	101	
73	1.15		1	446	487	484	92	92	
74	1.54		1	463	534	530	87	87	
75	2.36		1	628	632	627	99	100	
76	3.37		1	790	755	747	105	106	
77	0.23	○	—	451	395	427	114	106	Bauschinger; identical sandstone cylinders, pressure parallel to bed. Bauschinger's average: $-S_M = 369 + 115 \frac{1}{n}$ at. Diagrammatic average: $400 + 116.4 \frac{1}{n}$ at.
78	0.28		—	467	401	433	117	108	
79	0.35		—	464	409	441	113	105	
80	0.41		—	427	416	448	103	95	
81	0.67		—	463	446	478	104	97	
82	1.10		—	480	495	528	97	91	
83	1.31		—	494	520	552	95	90	
84	2.04		—	602	604	637	100	95	
85	2.70		—	806	680	714	118	113	

This table also contains a comparison of the values of differences between the observed values of $-S_M$ and the values deduced from the formulæ given. The formula deduced by B a u s c h i n g e r by the method of least squares does not always agree with those deduced by myself under conditions stated in the source (*L 135*) from the diagrammatic averages, but the discrepancies are not excessive, and I believe I may claim for the diagrammatic deductions the advantages of better illustration and unfettered consideration of the importance of individual values, at least as long as it is a question of practical utilization of results.

165. Verification of the type of formula given in (*163*) for the reduction of results obtained from prisms of variable shape to the prism of square section has not been obtained invariably. The tests must be greatly multiplied for this purpose; perhaps shape alone is not the only determinant, but the peculiarity of the material may also exert its influence.

a. My individual tests (*L 135*), made for the purpose of confirming B a u s c h i n g e r's formula for value of γ, on cast-iron prisms of different sections and length ratios, caused me to enunciate the following relations. An attempt to use the method of diagrammatic averages to determine values of γ as shown in Fig. 108 gave, when using B a u s c h i n g e r's results of tests for prisms of rectangular and circular section cut from a slab of fine-grained yellow sandstone (tests 68–85, Table 3 and Fig. *7c*, *L 2*, part 6)

$$\left.\begin{array}{ll}\text{for the square } S_\square = 353 + 111\frac{1}{n} \\ \text{for the circle } \quad S_\circ = 392 + 122.3\frac{1}{8}\end{array}\right\} m = \frac{\alpha}{\beta} = 3.18,$$

and correspondingly for the proportion:

$$\frac{S_\circ}{S_\square} = \gamma = \frac{392}{353} = \frac{122.3}{111} = 1.11,$$

hence very nearly the approximation given by B a u s c h i n g e r $\gamma' = 1.13$.

When taking the values for cubes and cylinders of ratio $\frac{1}{n} = 1$, in the case of my own tests of hard lead:

$$\gamma = \frac{S_{\circ}}{S_{\square}} = \frac{830}{773} = 1.07,$$

and by substituting the values obtained from the diagram of averages $\left(S_M = 663 + 130.4\frac{1}{n}\right)$:

$$\gamma = \frac{S_{\circ}}{S_{\square}} = \frac{830}{663 + 130} = 1.05.$$

b. My tests of cast iron (*L 135*) gave the following formulæ:

$$S_{\square} = 4190 + 1437\frac{1}{n}, \quad \text{and}$$

$$S_{\circ} = 4320 + 1417\frac{1}{n}.$$

These two equations can in no case give the Bauschinger results; when the results obtained from prisms of rectangular section are also taken into account, the conclusion will even be reached that equations obtained from my tests must take a different form in order that they agree, even approximately with the results found. The diagrammatic averages (Figs. 11 and 12 of the source) show the curves representing individual groups of results of tests obtained from rectangular prism of varying sectional ratio t/w between 1 and 12 to be almost parallel. The several series of tests gave the following approximations:

$$w/t = 1 \qquad S = 4190 + 1437\frac{1}{n}$$

$$w/t = 1 \qquad S = 4250 + 1557\frac{1}{n}$$

$$w/t = 1.15 \qquad S = 4570 + 1403\frac{1}{n}$$

$$w/t = 2.00 \qquad S = 4280 + 1467\frac{1}{n}$$

$$w/t = 4.00 \qquad S = 3900 + 1533\frac{1}{n}$$

$w/t = 8.00$ Results of tests show great discrepancies.

$$w/t = 12.00 \qquad S = 3460 + 1417\frac{1}{n}.$$

If the values of α and β be plotted according to increasing values of w/t as in Fig. 109, the systematic changes of lines α and β, but especially of α, will be readily recognized. The value of β may perhaps be considered to be independent of w/t. The mean value of β as deduced from the foregoing series is

$$\beta = 1469.$$

When it is investigated how the value of α as obtained from Bauschinger's value of γ would be modified by increasing values of w/t, it is possible, by use of values of γ in Sections 163 and the approximate value of $\alpha = 4400$ at. for the square section, to plot the dotted line in Fig. 109 for values of α from calculation, which agree very well with the values obtained by diagrammatic averages. Hence, as a rough approximation, for the cast iron tested (ordinary machinery castings) (when $t = 1$) we may assume:

$$S_M = \alpha\gamma + \beta\frac{1}{n} \quad \text{and} \quad = 4400\sqrt{\frac{\sqrt{w}}{\frac{1}{2}(w+1)}} + 1469\frac{1}{n}.$$

c. I have made several series of tests of tubular-shaped bodies, in one of which the external diameter d remained the same, while length l and internal diameter d_1 varied; in the second series both diameters increased in such manner that cross-sectional area of metal a on the length l remained constant (*L 135*, tests 193–231).

Using the results in these cases as was done in those above described, diagrammatic averages will give the following values for the first series:

for $d_1 = 0.00$ in. $\qquad S_M = 4160 + 1382\frac{1}{n}$

" $d_1 = 0.21$ in. (0.55 cm) $\qquad S_M = 4130 + 1204\frac{1}{n}$

" $d_1 = 0.43$ in. (1.1 cm) $\qquad S_M = 4120 + 1040\frac{1}{n}$

" $d_1 = 0.66$ in. (1.69 cm) $\qquad S_M = 4520 + 662\frac{1}{n}$

" $d_1 = 0.88$ in. (2.26 cm) $\qquad S_M = 4220 + 600\frac{1}{n}$.

It is evident that α remains constant in this case, and that β is variable (only the next to last series is somewhat discrepant). If the average is found for β as in Fig. 109, we shall obtain (Fig. 14 in the source) the equation:

$$S_M = \alpha + \beta\frac{1}{n}\sqrt{\frac{d - d_1}{d}} = 4230 + 1380\frac{1}{n}\sqrt{\frac{d - d_1}{d}},$$

in which 4230 is the average of the above comparison.

From the series, obtained from tubular pieces of identical a and l, but varying d and d_1, I obtained the equation:

$$S_M = 4400 + 1400\frac{1}{n}\sqrt{\frac{d - d_1}{d}}.$$

Comparing the equations for circular and annular sections we shall have

for the circle $\quad S_M = 4320 + 1417\frac{1}{n}$

$$\text{for the annulus } S_M = 4230 + 1380\frac{1}{n}\sqrt{\frac{d - d_1}{d}}$$

$$\text{and also} \qquad S_M = 4400 + 1400\frac{1}{n}\sqrt{\frac{d - d_1}{d}},$$

and the mean values from these will be:

$$\alpha = 4317 \quad \text{and} \quad \beta = 1399.$$

Therefore, according to my tests of cast iron (as a rough approximation) of square section:

$$S_M = \alpha\gamma + \beta\frac{1}{n} = 4400.1 + 1469\frac{1}{n},$$

and for the cylinder:

$$S_M = \alpha + \beta\frac{1}{n}\gamma = 4317 + .1399\frac{1}{n}.1;$$

for the length ratio $\frac{1}{n} = 1$:

$$\frac{S_{M\bigcirc}}{S_{M\square}} = \frac{4317 + 1399}{4400 + 1469} = \frac{5716}{5869} = 0.974,$$

while from the three values which are directly comparable we find:

$$\frac{1}{n} = 0.20, \qquad 1.00 \text{ and } 2.00,$$

$$\frac{S_{M\bigcirc}}{S_{M\square}} = 0.945, \quad 1.23 \text{ and } 0.954.$$

This shows that comparison of cylindrical and square sections of cast iron according to Bauschinger's coefficients is not yet possible. It certainly requires additional series of tests to explain existing contradictions, which must also include other materials.

166. According to the law of similarity, bodies geometrically similar must suffer similar deformations, i.e.,

similar crushing $-e_1$ during the crushing-test, under like stress. Kick (*L 100*, p. 43) has communicated several observations of this fact, which are reproduced in Table 19.

Table 19. Crushing of Geometrically Similar Bodies under Equal Crushing-stress.

Kick's results of tests have been reduced to $-S$ and $-e_1$.

a. Cylinder of plastic porcelain-clay, $d = 2$ in. (5.1 cm) and 1.36 in. (3.5 cm); and $l = 2.57$ in. (6.6 cm) and 1.72 in. (4.4 cm).

Crushing-stress $-S$ at. =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Shortening. $-e_1$, $d = 2$ in.	0.000	0.050	0.119	0.203	0.297	0.396	0.474	0.525	0.563	0.592	0.614
$d = 1.36$ in.	0.000	0.054	0.125	0.213	0.310	0.409	0.473	0.516	0.548	0.574	0.598

b. Cylinder of copper $d = 0.7$ (1.8 cm); 0.58 (1.5 cm); 0.39 (1 cm); $l = 0.7$; 0.58; 0.39.

$-S$ at. =	0	1000	2000	3000	4000	5000	6000	7000	7870	8000	
Shortening. $-e_1$, $d = 0.70$ in.	0.000	0.027	0.069	0.132	0.208	0.284	0.358	0.420	0.457	0.462	
$d = 0.58$ in.	The diagram is almost identical with that of the previous.*										
$d = 0.39$ in.	—	—	—	—	—	—	—	—	0.460	—	

* The individual values are not given in the original report.

It is certainly desirable to increase the number of corroborative tests here given.

The following problem is submitted to my students for practical solution.

Problem: The effect of shape on results of crushing-tests is to be determined using low steel (Flusseisen) test-pieces of circular and square sections.

Three series of test-pieces having proportions given below were available:

$$\frac{1}{n} = \sqrt{a/l} = 0.2;\ 0.4;\ 0.8;\ 1.0;\ 1.33;\ \text{and}\ \ 2.00.$$

Series *a* had square section; *b* and *c* were circular. Sectional areas of *a* and *b* were almost identical, $a = 1.04$ sq. in. (6.71 sq. cm) to 1.05 (6.76 sq. cm); and in series *c*, *a* varied from 1.317 sq. in. (8.50 sq. cm) to 1.325 sq. in. (8.55 sq. cm). So as not to make the matter more difficult for the

always more or less inexperienced investigators, the 100-ton Pohlmeyer machine was used, and observations of crushing were directed to be made not directly on the test-piece, but on the pressure-platens. The elastic distortions of cross-heads and straining-screws under the loads applied, as well as the amount of crushing of the platens, affected the results, but the influence of these errors was according to known laws, which can be easily calculated, for which corrections could have been applied when comparing results. Below I give the final results without consideration of the stated sources of errors.

As will be seen from Table 20, the amounts of crushing $-e\%$ under equal stress $-S$ are almost equal in case of

able 20. Influence of Shape of Test-piece on Crushing — $e\%$ in Crushing-tests.

eries.	a	b	c	a	b	c	a	b	c
m d or	□	○	○	□	○	○	□	○	○
cm,	2.59	2.93	3.29	2.59	2.93	3.30	2.59	2.93	3.30
q. cm,	6.71	6.74	8.50	6.71	6.74	8.55	6.71	6.74	8.55
cm	1.30	1.30	1.47	1.95	1.96	2.20	2.59	2.58	2.93
a/l	2.00			1.33			1.00		
a/u/4	1	1.06	1.06	1	1.06	1.06	1	1.06	1.06
1 at.	$-e\%\ 10^{-3}$			$-e\%\ 10^{-3}$			$-e\%\ 10^{-3}$		
	0	0	0	0	0	0	0	0	0
	13	12	11	15	13	8	10	9	11
	32	30	27	39	29	22	25	21	19
	57	54	56	67	54	42	57	48	47
	99	88	82	105	87	74	93	79	82
	157	134	140	156	128	113	144	122	127
	223	181	180	210	180	164	204	174	178
	283	235	246	269	234	217	264	227	235
	336	289	299	321	289	273	324	285	290
	383	338	350	370	342	324	377	335	345
	425	383	395	411	391	371	422	382	390
	465	419	(435)	450	433	413	460	428	433
	499	—	(472)	486	472	450	497	457	467
	533	—	—	518	507	—	528	490	—
	563	—	—	547	532	—	557	529	—
	582	—	—	573	—	—	580	542	—
at. =	—	—	—	—	—	—	2160	—	2340
-3 =	—	—	—	—	—	—	0.027	—	0.024

eries.	a	b	c	a	b	c	a	b	
m d or	□	○	○	□	○	○	□	○	(
cm,	2.60	2.93	3.30	2.60	2.93	3.30	2.60	2.93	3
q. cm,	6.76	6.74	8.55	6.76	6.74	8.55	6.76	6.74	8.
cm	3.25	3.24	3.64	6.50	6.49	7.32	13.0	13.0	14.
a/l	0.80			0.40			0.20		
a/u/4	1	1.06	1.06	1	1.06	1.06	1	1.06	1.
1 at.	$-e\%\ 10^{-3}$			$-e\%\ 10^{-3}$			$-e\%\ 10^{-3}$		
	0	0	0	0	0	0	0	0	
	7	7	7	4	3	3	4	3	
	18	18	18	10	7	5	8	4	
	51	46	46	47	33	26	18	27	3
	89	87	87	87	62	50			
	141	121	121						
	202	176	178						
	261	235	237						
	321	294	297						
	376	345	352						
	422	397	399						
	467	449	448						
	504	478	—						
	536	522	—						
	562	541	—						
	582	565	—						
at. =	2150	(2690)*	2300	2190	2380	2320	—	2230	231
-3 =	—	(0.040)*	—	0.012	—	0.011	—	0.005	—

* Uncertain; probably already exceeded.

geometrically similar prisms (b and c). They are smaller in case of circular sections than in square sections of equal length-ratio $\frac{1}{n}$. When the test-pieces did not depart greatly

from the length-ratio $\frac{1}{n} = 1$, the crushing $-e\%$ was but slightly affected. If the diagrammatic averages of values of the three series of results be obtained (by plotting them one upon the other and then drawing the average curve by eye-sight) a, b and c, Fig. 110, it will be found that lines b and c coincide, and that a is similar. In Fig. 110 the proportions of $-e\%_{\bigcirc}$ and $-e\%_{\square}$ for equal stress are also plotted; it will be found that $\frac{-e\%_{\bigcirc}}{-e\%_{\square}}$ between values 0.82 and 0.97 increases with stress $-S$. Hence the ratio of stress for equal deformations would be approximately:

$$\frac{-S_{\bigcirc}}{-S_{\square}} = \frac{1}{0.82} \text{ to } \frac{1}{0.97} = 1.22 \text{ to } 1.03,$$

which would agree approximately with the values of γ given by Bauschinger.

11. On the Shapes of Test-pieces to be used in the Crushing-test.

167. Crushing-tests are usually made on cubical or cylindrical test-pieces; the latter usually have a length $l =$ diameter d. The previous discussion will, however, show that a much better insight into the properties of materials would be obtained if such shapes of test-pieces were selected which will permit the determination of the material-constants α and β from the results of tests. For this purpose it would suffice to use a series of five test-pieces of length-ratio

$$\frac{1}{n} = 0.25,\ 0.5,\ 1.0,\ 2.5, \text{ and } 5; \text{ i.e.,}$$

$$l = \quad 4, \quad 2, \quad 1, \quad 0.4, \text{ and } 0.2\sqrt{a}.$$

In order to obtain a reliable average, it will in any event be necessary to make a number of tests (5 of metals and 10

of stone and cements). Hence it is just as convenient to use above ratios instead of making all pieces of the same dimensions. If possible it would be well to test square as well as cylindrical sections; the square sections deserve the preference as the standard, even though their preparation would be slightly more troublesome than that of cylinders.

The dimensions of sections to be used must depend upon the capacity of testing-machine available and the peculiarities of the material to be tested. In case of metals, length of side is generally from 0.8 in. (2 cm) to 1.2 in. (3 cm); in bond materials 2.8 in. (7 cm) or about $7\frac{3}{4}$ sq. in. (50 sq. cm) section of pressure-surface; for stone smaller cubes are used, depending upon their relative crushing-strength, usually about 2 in. sq. (5 cm); and brick is usually tested flat as a whole, or sawed into halves and superposed with a joint of Portland cement, producing an approximate cube applying pressure on top. The latter method has lately been introduced almost universally in the German official testing laboratories, on the recommendation of the "Conferences for Unification of Methods of Testing." Concrete should never be tested in blocks less than 8 in. cube, and even larger blocks should be used if the capacity of testing-machines make it possible. The Charlottenburg Laboratory uses cubes of 16 to 20 in. (40–50 cm) whenever possible. Bach uses (*L 136*) cylinders of 10 in. diam. (25 cm) and 10 or 40 in. (25 or 100 cm) length for the determination of the elastic properties of concrete.

a. As previously stated in (*104*) the character of pressure-surfaces plays an important part in crushing-tests. These surfaces must be finished plane or nicely surfaced. For this reason it is customary to cover the surfaces of stone having rough porous surfaces or uneven sides, and the properties of which would be changed by planing or grinding, with a coating of cement or mortar, thus producing a plane pressure-surface. This is done especially when testing brick. To do this (according to Bauschinger's proposition) the cubes

formed by cementing together the sawed half-bricks, are placed on a table between two boards (see Fig. 111), whose upper edges are parallel to the surface of the table. The boards are so clamped to the blocks that they project above them slightly. The Portland-cement paste, which is then poured on top of the blocks, is scraped off by a straight-edge immediately set commences, flush with the edges of the boards, thus forming a layer of cement from 0 2 to 0.4 in. (.5 to 1.0 cm) thick, with a plane upper surface. After complete setting the layer of cement is sawed through in the joints, and the opposite sides are then prepared in the same manner. Then both surfaces are ground plane.

b. When using this method it must, however, not be forgotten that the production and use of such cubes by no means insures the attainment of uniformity of crushing-resistance, as would be found with a homogeneous cube of brick material. Bodies geometrically similar and of the same material by no means show the same crushing-resistance if in one case they are monolithic and in others composite.

Vicat, Bauschinger, and others (*L 135*) investigated this case. Vicat found in case of cubes of gypsum built up as shown in Figs. 112, 113 and 114, that the crushing-strength compared to that of a monolith was as follows:

Cube of	1	2	4	8 pieces
Ratio of S_M	1	0.94	0.89	0.88

Whether these differences disappear in case the separate blocks be united by bond materials so as to form monolithic blocks can only be determined by actual tests.

Bauschinger refers to such tests (*L 2*, Part 10, p. 7 et seq). He says that he occasionally found greater crushing-resistance of two half-bricks cemented together* than of whole bricks with surfaces smoothed by cement and tested with layers of

* According to (*162*), $-S_M$ should actually decrease with decreasing $\frac{1}{n}$.

felt placed between the brick and the pressure-platens. "This result, which on first sight appears remarkable," says Bauschinger, "may perhaps be explained by the use of felt intercalations in my earlier tests, and perhaps also by the different character of the mortar-bonds" (neat cement in case of cubical blocks, and mortar of 1 cement, 3 sand in his earlier tests). Further study of this question would no doubt be of great value. (Compare *150*.)

b. Bending-resistance.*

1. Definitions.

168. Transverse tests are used only to a limited extent in the real art of testing materials, and in these cases the attempt is made to simplify the procedure as much as possible. It will therefore suffice to discuss the conditions for these simple cases, and to consider the phenomena occurring during the tests. Books on the Resistance of Materials, such as that of Bach (*L 137*), which I shall follow closely, moreover discuss the theory of bending and the difficult cases most fully.

Let a prismatic body (Fig. 115) of length l be fixed at one end, A, and loaded at the centre of gravity of its section at the other end, B, by a force P which lies in the plane of one of the principal axes of the section and the centre-line of the bar. The force P produces a moment

$$M = P(l - x)$$

in the section 1 at a distance x from the point A, and also a force P, which for the present shall be neglected in the fol-

* Throughout the book I shall use the words "bending" and "deflection" when speaking of "bending" or "transverse" tests, while the term "flexure" shall invariably refer to the "thrust-test." Bending or deflection relates to deformation in one plane or direction, and then generally in a continuous manner produced by an external force applied in the plane of deflection produced.

"Flexure," on the other hand, is produced by a secondary resultant of a force applied at right angles to the plane of deflection.—Gus. C. Henning.

lowing discussion, so that the acting external forces for section 1 may be replaced by a force couple.

The force P of the couple tends to distort the body; the body bends.

169. Under the assumption that the planes of section of the body, originally considered vertical to the axis AB, remain plane and vertical to the axis even after bending, two adjoining sections 1 and 2, separated by the distance dx (Figs. 116 and 117), can no longer be parallel after bending. Supposing the body to be composed of individual layers PP parallel to the axis, one of these layers, say OO, may retain its original length dx during bending, while the higher layers, say PP, suffer extension and the lower must undergo crushing, as the sections must remain planes even after bending. The distance of the projection of the traces of two planes 1 and 2 from the layer $OO = r$, Fig. 117, is the radius of curvature of the axis of the bar. The extension of the layer of fibres PP may be stated:

$$e_1 = \frac{\overline{P_1P_2'} - \overline{P_1P_2}}{P_1P_2} = \frac{\overline{P_1P_2'}}{\overline{O_1O_2}} - 1, \quad \text{or} \quad \frac{\overline{P_1P_2'}}{\overline{O_1O_2}} = \frac{r+\eta}{r},$$

when η is the distance of layer $\overline{PP}$ from layer $\overline{OO}$.

Hence $$e_1 = \frac{r+\eta}{r} - 1 = \frac{\eta}{r}$$

on the convex side of the bar, and

$$-e_1 = -\frac{\eta}{r}$$

on the concave side.

Under the supposition that the fibres exert no influence on each other, or that secondary forces are excluded, we can determine the stress due to deformations of fibres, from previous considerations (*34*),

$$S = \frac{e_1}{e_f}, \quad \text{and as } e_1 = \frac{\eta}{r},$$

we obtain

$$S = \frac{1}{e_f} \cdot \frac{\eta}{r} \cdot \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 14$$

170. The internal forces, the stress S, must be equal to zero, and in equilibrium with the external forces, moment M. Hence the sum of stresses must $= 0$ and their moment $= M$.

When the strip PP in Fig. 118, of width z and thickness $d\eta$, or $da = zd\eta$, the first condition to be fulfilled to make the sum of stress $= 0$ is expressed by $\int Sda = 0$ when integration includes the entire section.

As S is a constant for each section and as

$$S = \frac{1}{e} \cdot \frac{\eta}{r} \text{ (Eq. 14), we shall have:}$$

$$\int \frac{1}{e_f} \eta da = 0.$$

When the factors of extension e_f of the material for tension and crushing are equal, we shall have within the proportional limit

$$\int \eta da = 0, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 15$$

which signifies that the layer of fibres in which the stress and extensions are $= 0$ passes through the centre of gravity of the section; this layer is also called the neutral plane; it is normal to the plane of application of the moment M. As this plane, according to supposition (*168*), contains one major axis of the section, the neutral plane must contain the other.

The second condition of equilibrium is that the moments of internal and external forces be equal, or

$$\int S da \eta = M,$$

and when $S = \frac{1}{e_f} \cdot \frac{\eta}{r}$ is substituted, supposing e_f to be equal for tension and crushing, we shall have:

$$M = \frac{1}{e_f S} \int \eta^2 da,$$

and when $\int \eta^2 da$, the moment of inertia of section referred to the neutral axis $\overline{OO}$, or

$$\int \eta^2 da = I, \text{ we shall have:}$$

$$M = \frac{I}{e_f S} \quad \text{or} \quad \frac{1}{S} = \frac{e_f M}{I} \quad . \quad . \quad . \quad 16$$

From equations 14 and 16:

$$S = \frac{1}{e_f} \cdot \frac{\eta}{r} \quad \text{and} \quad \frac{1}{r} = e_f \frac{M}{I} \quad \text{and}$$

$$S = \frac{M}{I} \eta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 17$$

Stress S is proportional to the distance η of the fibres from the neutral axis; they are greatest in the extreme or outer layers of the section at distance $\eta = b_z$ or b_d, Fig. 119.

Correspondingly:

$$\left.\begin{array}{ll} \text{Maximum tension-stress} + S = \frac{M}{I} b_z \\ \text{“} \qquad \text{crushing-stress} - S = -\frac{M}{I} b_d \end{array}\right\} \quad . \quad 18$$

171. With the same approximation with which the reciprocal of the radius of curvature may be represented by

the second differential of y referred to de_f : $\frac{1}{r} = \pm \frac{d^2y}{dx^2}$, we may also, according to equation 16, place:

$$M = \pm \frac{Id^2y}{e_f dx^2}, \quad \text{or}$$

$$L(l - x) = \frac{Id^2y}{e_f dx^2}.$$

This shows that, under the previous assumption that e_f for tension is equal to that for crushing, and hence that the section of bar will remain uniform over the total length l, and also that I is a constant, by integration we have:

$$\frac{I}{e_f} \cdot \frac{dy}{dx} = L\left(lx - \frac{x^2}{2}\right) + C.$$

As the curved axis of bar, i.e., the elastic line, is tangent to the bar axis, initially straight (Fig. 120) at the fixed point (an assumption which is, however, only exceptionally accurate), we have:

for $x = 0$; $\frac{dy}{dx} = 0$ and also $C = 0$, and hence

$$\frac{dy}{dx} = \frac{e_f}{I} L\left(l - \frac{x}{2}\right)x. \quad . \quad . \quad . \quad . \quad . \quad a$$

From this equation the angle β between the tangent to the elastic curve and the original axis of bar can be calculated for every point of the elastic curve (Fig. 120).

For the free end B of the bar, as $x = l$, we shall have from Eq. a:

$$\text{tang}\ \beta = \frac{e_f}{I} . L\left(l - \frac{l}{2}\right)l = \frac{e_f}{2I} Ll^2;$$

and as β is always a very small angle, we may say:

$$\beta = \frac{e_f}{2I} Ll^2.$$

From Eq. a we shall have

$$y = 0 \quad \text{for} \quad x = 0.$$

By integrating, the equation of the elastic curve will be:

$$y = \frac{e_f}{I}\frac{P}{2}\left(l - \frac{l}{3}\right)l^2 \quad \text{or}$$

Deflection δ at the end B for $x = l$ will be:

$$\delta = \frac{e_f}{I}\frac{P}{2}\left(l - \frac{l}{3}\right)l^2, \quad \text{or}$$

$$\delta = \frac{e_f}{I}\frac{P}{3}l^3. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 19$$

172. For bending-tests the bars are almost invariably supported at both ends, and loaded at the centre by a load L. In this case the bar may be considered as fixed at the centre and loaded at the end by a force $\frac{L}{2}$ in the opposite direction, Fig. 121.

Hence we may write:

$$M = \frac{L}{2}\cdot\frac{l}{2} = \frac{Ll}{4}, \text{ and according to Eq. 18}$$

$$\pm S = \frac{Ll\,.\,b}{4I}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 20$$

Under the same assumptions, the deflection δ at centre of bar will be found by substituting in Eq. 19 for $l = \frac{l}{2}$, and $L = \frac{L}{2}$:

$$\delta = \frac{e_f}{I}\cdot\frac{L}{2}\cdot\frac{1}{3}\cdot\frac{l^3}{2^3} \quad \text{or}$$

$$\delta = \frac{e_f}{48}\cdot\frac{Ll^3}{I}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 21$$

a. Although these formulæ for deflection are valid only for the condition of materials within the proportional limit, during which e_f is constant, they are nevertheless, for simplicity's sake, frequently used in testing material as though they were applicable to rupture, or at least up to excessive flexure.

Moreover, the deduction of these formulæ is based upon a number of assumptions, whose correctness was presumed without question. It will be necessary to establish how far these assumptions are correct, and to which degree their incorrectness affects the accuracy of the bending-tests. In this I follow Bach (*L 137*, § 20).

b. The first assumption was that the external forces acting on the body produced but a single couple for each cross-section, whose plane intersects the latter normally to one of its two principal axes. The second assumption was that the fibres composing the bar do not coact upon each other. Thirdly, the cross-sections originally plane and normal to the axis of bar were to remain plane and normal to bar-axis after bending. Fourthly, the factor of extension e_f was to remain equal for tension and crushing and constant up to the proportional limit.

The degree of admissibility of these assumptions may be most readily determined by imagining, as was done by Bach (*L 137*, § 20), that the body be so constructed as to actually fulfil the assumptions. Thus Bach supposed the body to be composed entirely of long spiral springs, all independent of each other, and rigidly connected to the end surfaces 1 and 2, Fig. 122. The couple P acts at 2 in the plane of symmetry (the plane of one principal axis, see Sect. 168), having a moment $M = P \,.\, a$. The plane 2 revolves about axis EE. The springs to the left are distended, those to the right shortened; the latter must not be able to deflect laterally. Extension and shortening e should be proportional

to the distance η from the axis EE. Hence we shall have, if l_g be the original length of spring:

$$e_1 = \frac{e}{l_g}.$$

If extension at distance $1 = e_1'$, then:

$$e_1 = e_1'\eta; \quad \text{and stress} \quad S = \frac{e_1'}{e_f}\eta,$$

and this corresponds, when the cross-section of the layer of fibres $= a_0$, to a force:

$$Sa_0 = \frac{e_1'}{e_f}\eta a_0.$$

In order to establish equilibrium, the sum of the internal forces must equal 0, or

$$\Sigma Sa_0 = \Sigma\frac{e_1'}{e_f}\,.\,\eta\,.\,a_0 = 0. \quad . \quad . \quad . \quad . \quad a$$

And the sum of their moments must be equal to moment of the applied force:

$$M = P\,.\,e_f, \quad \text{or}$$

$$\Sigma Sa_0\eta = \Sigma\frac{e_1'}{e_f}\,.\,a_0\,.\,\eta^2 = M. \quad . \quad . \quad . \quad b$$

As e_f may be considered equal for tension and crushing, the first equation (a) will give:

$$\Sigma a_0\eta = 0,$$

i.e., the axis of 0, EE, passes through the centre of gravity of all fibre-sections and is the second principal axis of the cross-section of bar. As

$$\Sigma a_0\eta^2 = I,$$

we shall have from Eq. b, under the same supposition as to e_f:

$$M = \frac{e_1'}{e_f}.I.$$

If e_z and e_d be the values of η for the extreme fibres, the stress to which they are subject will be:

$$+S = \frac{e_1'}{e_f} . b_z \quad \text{or} \quad -S = -\frac{e_1'}{e_f} . b_d, \text{ and hence:}$$

$$\frac{e_1'}{e_f} = +\frac{S}{b_z} \quad \text{or} \quad \frac{e_1'}{e_f} = -\frac{S}{b_d}.$$

The couple PP does not produce deflection of the bar, which remains straight. The cross-sectional plane ceases to remain normal to the axis of bar. All cross-sections, moreover, intersect in the line whose projection M, Fig. 123, is at a distance r from the neutral layer EE. Hence r is no longer the radius of curvature, M no longer the center of bending, because, as the bar remains straight, the radius of curvature is ∞.

The relations (given in Sect. 169):

$$e_1 = \frac{r + \eta}{r} - 1 = \frac{\eta}{r},$$

derived for the curved bar under the supposition that cross-sections remain normal to the axis, also apply when the axis remains straight and this assumption is not met.

As r in that case is no longer the radius of curvature, $+\frac{d^2\eta}{dx^2}$ cannot be substituted for $\frac{1}{r}$.

c. The first supposition, that but one couple represents the force applied, is as a rule incorrect; the generation of the bending-moment almost invariably requires secondary forces. A distortion is generally present, whose influence is, however, unimportant in many cases. Local stress of material due to bearings and influence of loading-devices is almost always present (*L 120*) and may produce effects similar to those of grips and holders in tension and crushing tests. During great deflection the friction between bearing and test-piece exerts a material influence, especially when heavy loads are

applied. Under these circumstances the unavoidable variation of length between bearings also has an effect on the result of the bending-test.

d. The second assumption, that the fibres exert no influence on each other, is by no means met by the bar which acts as a unit, because there is always a change of cross-section during change of length of fibres, as shown in Sections 43 and 59; the greater the extensions the greater the change of cross-section; hence they are greatest in the extreme layers and $= 0$ at the neutral layer of fibres. The fibres must change their position relative to the neutral layer during bending, because of the change of section, and must co-act with each other. Every constraint against change of cross-section increases resistance to tension and crushing (*103*), and hence the relation

$$S = \frac{e_1}{e_f}$$

is no longer strictly applicable.

The fibres coact not only because of change of cross-section, but also because of change of length which they undergo according to their distance η from the neutral layer, and which produces a tendency to distortion between contiguous fibres.

This mutual coaction of fibres is different in degree in different cross-sections. In section 1–1 of the two sections A and B, Fig. 124, the fibres in A are to a great extent free (unconstrained), while this is not the case in B. Hence these fibres are less affected in A, and hence they will conform to the theory more closely. Therefore if two bars of the same material be shaped as A and B, and the maximum stress be calculated from the results of tests, by use of the equation

$$M = S\frac{L}{b_s},$$

somewhat greater bending-resistance must be found in case of B than in A.

The more nearly the section takes the shape of two narrow layers of fibres parallel to the (ideal) neutral plane, Fig. 125, the more perfectly will the assumption of independence of individual fibres be fulfilled.

e. The third assumption, that cross-sections shall remain plane, is also not strictly accurate, because the distorting stress usually coincident with the bending moments acts on the bending of the sections.

However, Bauschinger, Bach, and others have proven by tests that cross-sectional planes remain plane and normal to the axis of bar in case of wrought iron of square sections, even when bending is carried considerably beyond the elastic limit. Hence the above assumption is to be considered accurate for bars mainly subject to transverse load.*

f. That the fourth assumption, that of equality of e_f for tension and crushing, and of stress, being below proportional limit, is only correct for certain materials, e.g., wrought iron and steel, has already been discussed in (*37*), p. 27.

173. Because, according to the foregoing, it must not be expected that the results of transverse tests can agree with theoretical deductions based on assumptions introduced for the purpose of simplifying the analysis, it must not also be expected that the calculations of tensile and crushing strength based on the results of bending-tests can agree with those deduced from tension and crushing tests (*L 105*, p. 41, No. 26, and p. 97, etc.).

The above reasons would appear to make it most advisable to deduce bending-stresses permissible when using the above-mentioned materials in construction, not from tension- and crushing-tests, but directly from bending-tests, or at least to determine those conditions which affect results according to

* However compare statements in (*382*), Fig. 261.

fixed laws, experimentally (*L 138*). From this it will appear that the results would of course depend more or less upon the shape of section.

174. It would, however, on the one hand, cause considerable expense and inconvenience to determine transverse strength of materials for all possible shapes of sections and methods of loading, and, on the other, consideration of all secondary considerations would involve such complexity that the assumptions above made (*168–171*) will for the time being be adhered to by the profession. The simple theory will no doubt be supplemented by accurate calculation in special cases alone, when conditions are such that their effect may be clearly foreseen. It will be necessary, as a rule, to see to it that transverse tests be carried out in such manner that positive bending-stress alone be produced.

We are therefore compelled to find the conditions for most favorable application of stress to the bars, and to select such shapes that directly comparable results be obtained by all investigators.

2. The Transverse Test.*

175. For the purpose of making a transverse test it is customary to give the test-pieces the simplest shapes, the moments of inertia I of which are found in all engineers' handbooks in the shape of calculated tables, or by which and the simple formula there also given they can be readily calculated. When complex shapes are used, their moments of inertia can be determined by approximations, or by use of a proper integrating planimeter. I shall not pursue these matters at this time, but revert to them at the end of the book.

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* The term "transverse test" shall be strictly adhered to, because it is in common use, and also because "bending-tests" refers to the shop test, hot or cold, universally.—G. C. Hg.

176. As previously stated (*172*), transverse tests are usually made as shown in Fig. 121, the bar being carried by two supports and loaded at the centre. It is customary to measure deflections δ at centre under loads L, increasing in intervals.

A diagram may be plotted from loads L and deflections δ, as in the tension-test, Fig. 126.

If e_f be constant for the material tested, then the deflection of the bar will be, according to Eq. 21,

$$\delta = \frac{e_f \cdot Ll^3}{48I}$$

proportional to the load, and as

$$S = \frac{Ll}{4I} \cdot b,$$

it is also proportional to stress S.

Hence the earlier part of the curve up to P will be a straight line. P is the proportional limit for bending. Beyond P the curve shows gradual change to the point Y, at which deflections suddenly increase under small increments of load. This point Y is called the yield- or bend-point, corresponding to the previously identified yield- or crushing-point (*37–39*) of the material. While some materials are ruptured when continuing the test beyond this point, or stress reaches a maximum, point M, Fig. 126, permitting the determination of breaking-stress, others cannot be ruptured by the greatest loads. In this case the yield-point, as in the case of the crushing-test, must serve as the qualifying factor in the properties of the material tested. In this case, also, the further progress of the test is frequently of interest to the technologist, because he can draw conclusions as to the workability of the material from its behavior.

177. As the points P, Y and M also appear as characteristic points in the transverse test, and the stress and deforma-

tion relative thereto are commonly used for the qualification of properties of materials, it is desirable here to use an abbreviated, ready, comprehensive notation. For this purpose the following notation will be hereafter used in this book when it is desired to indicate from which kind of loading the values given were derived, or to which they refer:

$$\left.\begin{array}{lll} S_{P,\,Y,\,M}; & e_{P,\,Y,\,M}; & \text{for tension-load} \\ -S_{P,\,Y,\,M}; & -e_{P,\,Y,\,M}; & \text{for crushing-load} \end{array}\right\} \text{derived from tension- or crushing-test.}$$

$$\left.\begin{array}{lll} S'_{P,\,Y,\,M}; & e'_{P,\,Y,\,M}; & \text{for tension-load} \\ -S'_{P,\,Y,\,M}; & -e'_{P,\,Y,\,M}; & \text{for crushing-load} \end{array}\right\} \text{derived from bending-test.}$$

Similarly S', e', etc., are the symbols for simple stress and extension, etc., as referred to the same.

178. As in the case of the tension- and crushing-test it may be of interest to study the behavior of the material under decrease of load and repetitive stress during the transverse test. These occurrences may again be illustrated by diagrams as in (*41*) by plotting lines of permanent (set) and of elastic deflection (resilience).

Residuary phenomena can also be studied by the transverse test, and the areas of diagrams may again serve, as was the case in the tension- and crushing-test, to determine the total and the specific work of deformation during deflection. (Compare *48–54*) (*L 137*, § 42, p. 215.)

179. Stress lines and figures also appear on the surfaces of the material, similar to those in tension- and crushing-tests (*88–90*), and the phenomena of fractures are also equally characteristic. I do not wish to discuss these details at this time, and shall reserve them for discussion in connection with impact transverse tests in (*272*), etc., and the fracture phenomena of repetitive tests (*333*, etc.).

180. What should be said about the actual method of making the test relates to a short description of methods of observations and of the apparatus used for precise measure-

ments; at this place, however, only general principles shall be presented.

In rough tests deflections are usually determined by measuring the deflection by means of a foot-rule, resting against a gauge or straight-edge or string, fixed in relation to the supports for the test-bar. But, as will be shown (*268*), the variation of distance between bearing-points, crushing of the latter, and under the point of application of the load L, cannot be readily prevented; it becomes necessary to use the utmost caution in making measurements of precision in order to avoid errors.

It is customary to make these measurements from the neutral axis as a base. B a u s c h i n g e r conceived a very beautiful apparatus for this purpose, the description of which will explain the essential elements requisite in measuring deflection. Fig. 127 shows the scheme of this apparatus. Two pairs of centre-punch marks, a and b, are made on the neutral axes of the sides of the test-bar, directly above the points of support, separated by a distance $=l_g$, and a third point, c midway between the others. They serve as bearings for the pointed screws carrying the three yokes. These yokes carry movable bars by hinges (not shown), their ends bearing on rollers R a b c of the roller-friction levers, moving the latter by friction whenever points a, b and c change their relative positions. The motion of levers z is read on the graduated arcs M. The ratio of multiplication (ratio of radius of rollers to radius of graduated arcs) is $\frac{1}{20}$ or $\frac{1}{50}$, so that, accordingly as the small or large rollers are used, readings of motion of punch-marks relative to the fixed points of roller carriers of approximately $\frac{1}{5000}$ in. ($\frac{1}{2000}$ cm) or $\frac{1}{12500}$ in. ($\frac{1}{5000}$ cm) are possible, as the arcs are divided into millimeters. The two lateral rollers a and c measure the motion over bearing-points, and c that of the motion of centre of bar; the difference of readings

$$c - \frac{a+b}{2} = \delta$$

therefore gives the actual deflection of the centre of bar. Great deflection of course produces change of length l_r. (Compare div. 5, *266–270*.)

By providing a straight-edge attached in such manner as to move unconstrainedly with the end punch-marks, the independent measurements of motion of these points may be avoided, the motion of middle centre-punch mark with reference to the straight-edge being alone determined.

When making transverse-tests of timber at the Charlottenburg Laboratory, the method is sometimes adopted of driving fine wire pins into the bar at points a and b (Fig. 127) in the neutral axis. A fine copper or steel wire (carding or florist's wire) is then stretched across the pins, tightened by means of weights at the ends. This wire acts as an indicator (cross-hair), passing over a millimeter-scale of paper mounted at point c. In this manner readings of about 0.01 in. (0.2 mm) may be made.

181. If the investigation relates to materials having very slight flexibility, or if the deflection is to be determined with great accuracy, mirror apparatus (*87*) may be used. A straight-edge L, provided with three points (a wood strip with three nails driven into it), one of which at the left end A rests above the point of support, while the two others are above the right support at B, is mounted on the test-bar so that distance between points at A and B is $= l_r$. Two very elastic angles, f and f_1 (Fig. 128), are attached to the bar and straight-edge, by some wax-resin-putty, at the centre. The mirror-spindle is then clamped between these two springs f and f_1, as was described in (*87*) for the tension-test. Readings are taken by telescope on scale M, as before. Deflections of about $\frac{1}{100000}$ in. ($\frac{1}{500000}$ cm) may thus be readily estimated. The total deflection in this case must, however, not exceed 0.02 in. (0.05 cm), but the method is a very satisfactory one in tests of stone, mortar, concrete, etc.

182. Intze employed a very interesting application of the

mirror to make a demonstration of deflection of a bar in every direction visual to his audience. He used a principle, previously applied however, to make precise determinations of deflections of a bar in a plane. The angle β (Fig. 120) between the elastic line and the original bar-axis, at the supports, is measured. A mirror is mounted on one end of the bar, and its angular motion is measured (Fig. 129). Intze supported the bar in such manner that it could be revolved about its axis while subjected to a definite load P. If a combination of lenses was then arranged so as to throw a pencil of light on the mirror which would reflect it focussed on the scale M, the double angle β could be read off or the scale, or marked on a strip of paper. If the bar (say an angle-iron) were then revolved as well as the paper or scale about the same axis OO, the angle β would vary in proportion to the difference of I for the section placed in different positions with relation to the axis. If these different points of light were then plotted on paper, the inertia-ellipse of the particular section of bar would be obtained.

183. In testing materials, as stated in *172* and *175*, the bar is supported on two bearings and loaded at the centre.

The results of transverse test are determined from equation :

$$S' = \frac{L \cdot l_e}{4I} \cdot b, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 20$$

which applies to S'_P, stress at proportional limit,

S'_Y, " " yield-point,

S'_M, " " maximum,

and also deflections δ at these points.

From the equations for deflection and the values of δ found, we shall have:

$$e'_f = 48\frac{I}{l_e^3}\frac{\delta}{L}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 22$$

or when the ratio $\frac{\delta}{l_g}$ represents the ratio of deflection, then

$$e'_f = 48\frac{I}{l_g^2 L}\cdot\frac{\delta}{l_g}. \quad . \quad . \quad . \quad . \quad . \quad . \quad 23$$

As the modulus of elasticity is $E = \frac{1}{e_f}$,

$$E' = \frac{1}{e_f} = \frac{l_g^2 L}{48 I}\cdot\frac{l_g}{\delta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 24$$

If the ratio of deflection produced by the unit of stress be called the unit of deflection, its value will be found from Eqs. 20 and 23 to be

$$\frac{\delta/l_g}{S} = \frac{e_f}{48}\frac{Ll_g^2}{I}\cdot\frac{4I}{Ll_g b} = \frac{e_f}{12}\cdot\frac{l_g}{b} \quad . \quad . \quad . \quad . \quad 25$$

The ratio of deflection is constant with e_f within the proportional limit, which is dependent upon the material, and also the ratio between length between supports (gauge-length) and the distance of the extreme fibre from the neutral axis.

3. Bending and the Law of Similarity.

184. Advantages may also be gained from the law of similarity in the case of transverse tests.

Kick enunciates this law for flexure as follows:

> "Bars of the same material, and of similar shape, when supported or fixed, and loaded in the same manner, require loads proportional to the cross-sectional area, to produce similar deflection." The words "when supported or fixed, and loaded in the same manner," may be easily misunderstood.

It is therefore necessary to call attention to the fact that they do not refer to the method of making the test in a most general way; but the dimensions of bearings particularly must have similar dimensions if the conditions of the law are to be complied with.

185. To establish the law, let us assume two bodies, A and A_1, geometrically similar and of prismatic section, Fig. 130. All values relating to A are written without, those referring to A_1 are with, an index 1.

In these two bodies the following ratios exist:

1) lengths, $\quad \dfrac{a}{a_1} = \dfrac{b}{b_1} = \dfrac{l_g}{l_{g1}} = \dfrac{1}{n}$;

2) surfaces, $\quad \dfrac{ab}{a_1 b_1} = \dfrac{f}{f_1} = \dfrac{1}{n^2}$;

3) volumes and weight, $\dfrac{J}{J_1} = \dfrac{W}{W_1} = \dfrac{1}{n^3}$.

4) moments of inertia, $\dfrac{I}{I_1} = \dfrac{1}{n^4}$.

When deflections are indicated by ratio of deflection, a similar deformation of A and A_1 is produced when

$$\frac{\delta}{l_g} = \frac{\delta_1}{l_{g1}},$$

for
$$\frac{\delta}{\delta_1} \text{ will } = \frac{l_g}{l_{g1}} = \frac{1}{n}.$$

From Eq. 23, for body A:

$$\frac{\delta}{l_g} = \frac{e_f}{48} \frac{L l_g^2}{I};$$

and for A_1:

$$\frac{\delta_1}{l_{g1}} = \frac{e_f}{48} \frac{L_1 l_{g1}^2}{I_1} \text{ or } = \frac{e_f}{48} \frac{L_1 l_g^2 n^2}{I n^4} = \frac{e_f}{48} \frac{L_1 l^2}{I} \frac{1}{n^2}.$$

From these two equations we shall have:

$$\frac{\delta \,.\, l_{g1}}{l_g \,.\, \delta_1} = 1 = \frac{e_f L l^2}{48 I} \cdot \frac{48 I n^2}{e_f \,.\, L_1 n^2} = \frac{L}{L_1} n^2.$$

Hence the same ratio of deflection, i.e., geometrically similar deformations, will be produced by loads which are as 1 to n^2, or as the cross-sectional areas.

The relation of stress is found from

$$S' = \frac{Ll_g}{4} \cdot \frac{b}{I};$$

and as $b_1 = bn$, and $L_1 = Ln^2$,

$$S_1' = \frac{L_1 lg_1 b_1}{4I_1} = \frac{Ln^2 l_g n}{4} \cdot \frac{bn}{In^4} = \frac{Ll_g}{4} \cdot \frac{b}{I};$$

hence $$\frac{S'}{S_1'} = 1, \text{ or:}$$

> Equal stress produces equal ratios of deflection in bodies geometrically similar.

Hence if stress S' and ratios of deflection δ/l_g be plotted for geometrically similar bodies, the curves obtained will coincide.

186. The law of similarity holds good, independently of the bending theory, for every deformation, elastic and permanent, and if its requirements do not seem to have been fulfilled during any test, although all fundamental requirements of similarity of conditions had been met, then the differences can only have been caused by differences in the material.

Hence, in order to obtain comparable results in such cases in which it is impossible to use bars of identical shape, it is recommended that at least geometrically similar bars be used.

In this case the load increments are to be proportional to the square of the dimensions of the length; hence the cross-sectional area and deflections are to be conveniently noted as ratio of deflection. The unit of deflection and factor of elongation e_f are then constants within the proportional limit, and the ratios of deflection beyond the elastic limit will also be

equal for like stress, as long as the test-pieces of different dimensions are cut from the same material under like conditions.

The importance of the introduction of uniform methods of test which are acceptable to the greatest possible number will again become apparent in this case. Tests by Bach (*L 138*) and also those by the Comm. Am. Soc. M. E. (Trans. A. S. M. E., 1885 et seq.) of cast-iron bars of different shapes prove in a most striking manner the slight value possessed by a report of a transverse test of cast iron when the sections used are not fully described, or when it is not stated whether the results of tests have been calculated as referred to the standard cross-section, i.e., the square or the circle, with use of the empirical factors.

These empirical factors are, however, still very few in number, and it is all the more important to multiply them, as it is by no means impossible that they depend upon external conditions (conditions of pouring, cooling, etc.). It is quite certain, however, that the ratio $S_M : S'_M$ for cast iron depends upon chemical composition.

[Note. The Reports of the Committee on Standard Tests and Methods of Testing Materials, A. S. M. E. (see Trans.), have demonstrated that chemical composition is of primary importance in controlling the physical properties of cast iron, but that shape of test-bar and conditions of melting and casting are of equal importance. A mere description of shape of test-piece has been found to be insufficient, as the surrounding influences, slow cooling, or possibility of chilling are all-important in their effect on the characteristics of physical properties of cast iron.—G. C. Hg.]

These considerations are of special value in the case of cast iron, because material is frequently and most undoubtedly appriately tested transversely by bending-test. In Germany the square bar 1.2 in. (3 cm) recommended by the Conferences on Unification of Methods of Testing, and 39¼ in. (1 m) between supports, is very largely used. This

bar should be introduced most generally, and where its use is impossible bars whose proportion of length to section is $\frac{l_g}{d} = 33.3$ should be used.

Moreover, the method of casting and the circumstance of pressure or absence of casting skin are of material influence on the results (*L 138*).

c. Thrust-resistance.*

1. Definitions.

187. Carrying out thrust-tests is really exceptional in the science of testing materials. Whenever a thrust-test is made it is generally a question of determining deformation (lateral flexure) of parts of structures under trial loads; e.g., to test supports, columns, struts, bridge members, etc., etc., rarely, however, to determine constants of materials.

I shall therefore refrain from developing the theories of thrust, but shall briefly state Euler's equations (*189*), which appear to remain the most important fundamentals for the theory of thrust. I refer to the books of Bach (*L 137*),

* The terms "thrust," "thrust-test," "thrust-resistance," shall be invariably used when reference is made to application of force longitudinally to the object, when the latter has a very great length-ratio $\frac{l_g}{d}$; the difference between this term and "crushing" lies in the fact that the latter refers to this length-ratio $\frac{l_g}{d}$, being very small in the latter case.

If this distinction be kept in mind no confusion will arise and the awkward and incorrect terms "compression," "compression-test," "compressive force," will be entirely avoided. Moreover, the confusion of the meaning of the term "compression," whether relating to force or to length, will not arise, especially as the terms "shortening" or "shorten" here used apply with equal correctness and clearness to both crushing- and thrust-tests. I am well aware of the general use of the term "compression-test," but refuse to be a party to the adoption or use of a term which among engineers and scientists should be considered unpardonable.—G. C. Hg.

Grashof (*L 139*), and others, or to the exhaustive tests of Bauschinger (*L 140*), Tetmajer (*L 141, 142*), and others for a more detailed study of the subject. Bauschinger reaches the conclusion that Euler's equations suffice for the theory of thrust; Zimmermann is of the same opinion. Land (*L 144*) lately published a pretty derivation of Euler's equations.

188. If a long prismatic bar be subjected to end pressure it will rarely ever bulge, as is the case with short bodies of same section, and assume barrel-shape, or show the phenomena of rupture described in (*125*). It will in fact almost invariably be flexed (bent laterally) in either direction, and the fracture will be similar to that obtained by the transverse test.

A long body is never mathematically straight; it is also almost impossible to grip it by the testing-machine in such manner that the centre of stress coincides with the axis through the centre of gravity. Likewise secondary stresses, due to defective bearing between pressure-surfaces, or the use of horizontal machines and consequent deflection produced by the dead weight, can hardly be obviated; they appear during the progress of the test. All these circumstances produce bending-stress additionally to the thrust-stress. The moment producing flexure is very small in case of short bodies, and the force L may also exceed the crushing-strength. But if the bodies become sufficiently long in relation to the section, the lever-arm of the bending-moment increases under effect of the force L acting in the direction of the axis, finally irresistibly, and the body is ruptured by flexure. Flexure usually occurs when the body is free to bend laterally, in the plane which has the least moment of inertia. If an appreciable deflection existed initially, which may be the case in long bodies tested horizontally, flexure usually occurs in the plane of this deflection in case of bodies having equal or nearly equal moments of inertia in different directions.

189. The development of the elastic curve during flexure

will vary according to the type of end bearing, and hence the force required to produce flexure will also vary accordingly. It is customary to distinguish four types of bearing.

a. The body is fixed at one end, as shown in Fig. 131, and the force L acts on the other end parallel to the original axis, but otherwise unconstrainedly; the free end of the bar may also move laterally without constraint. This case hardly ever arises in testing.

b. The body is free to move (hinged) at both ends, as in Fig. 132 (bearings on knife-edges, centres or ball joints), but they are so guided that the direction of force always passes through the centre of supports. This case is frequently used in testing.

c. The body is fixed at one end, as in case *a*, and hinged at the other, as in case *b* and shown in Fig. 133.

d. The body is fixed at both ends, but these are guided in such manner that the direction of force always passes through centre of support. Frequently used in testing.

The limiting loads for these four cases, under which, according to Bauschinger, the initial deformation, as well as the gradually increasing flexure produced by increasing loads, suddenly becomes immeasurable,* are given by Euler's equations as below, for each method of loading, as follows:

* Bach (L *137*, § 24) deduced the value for flexure for case *a* as follows:

$$y = a\,\frac{1 - \cos\left(x\sqrt{\frac{e_f L}{I}}\right)}{\cos\left(l_g \cdot \sqrt{\frac{e_f L}{I}}\right)} \quad \text{and}$$

gives a very pretty example by calculating flexure of a bar 40 in. long and 4 in. diam., with L gradually increasing. If a be the small leverage at which the force L acts producing the bending moment, he finds

for $L =$	5	10	15	20	22.5	24.7 at.
flexure of free end of bar	$0.32a$	$0.85a$	$1.95a$	$5.54a$	$13.16a$	∞a—failure.

For that shown by Fig. 131:

$$a)\ L = \frac{\pi^2}{4}\frac{1}{e_f}\frac{I}{l_g^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad 26$$

in which e_f = factor of elongation; l_g = test-length; I = least moment of inertia of section.

For Fig. 132:

$$b)\ L = \pi^2\frac{1}{e_f}\frac{I}{l_g^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad 27$$

For Fig. 133:

$$c)\ L = 2\pi^2\frac{1}{e_f}\frac{I}{l_g^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 28$$

And for Fig. 134:

$$d)\ L = 4\pi^2\frac{1}{e_f}\frac{I}{l_g^2} \quad . \quad . \quad . \quad . \quad . \quad 29$$

When using these formulæ for calculations, it should be remembered that objections to the derivation of the bending theory, similar to those stated in (*172*), may be urged against the assumptions made. It should never be forgotten that these typical methods of loading are never quite realized, and that they are rather modifications from one to the other; that in fact such modifications may occur suddenly during test. The constructor must consider the possibilities of each case by itself. For these reasons the empirical formulæ do not always possess the value which their agreement with results of tests from which they were derived would seem to indicate.

2. The Thrust-test.

190. Holding-devices for thrust-tests must be designed in such manner that the body must undergo flexure as nearly as possible in conformity with one of the types shown in Figs. 131–134. For this reason either the body itself or its bearing-devices are provided with knife-edges, points, pins or balls. In

the latter case provision is sometimes made to fix the bearing-plates firmly after adjustment by means of four set-screws.

Fig. 38 (*73*) shows the pressure holding-devices for the Werder machine. The platen moves freely in the spherical bearing (although resisted by the friction between bearing-surfaces), or it can be fixed by the four set screws.

191. Measurement of flexure is generally a very inconvenient matter. It is simplest in cases in which the test-pieces are themselves provided with knife-edges, points, pins or balls for bearings, and when it is certain that the bearings suffer no lateral displacement. This will, however, rarely be the case, and it will therefore be necessary to presuppose lateral displacement when making measurements of precision. If displacements of bearings be precluded, it will suffice to measure flexure at the centre of length, referred to two points fixed in space, in such manner that the motion in the direction of the two R. A. axes of the middle section be determined. In the second case similar measurements should also be made in planes as near as possible to the bearing-surfaces, and the actual flexure of test-piece then be determined either mathematically or graphically; in fact a tedious but a necessary procedure.

192. Bauschinger also constructed very satisfactory apparatus for the above object, shown in scheme in Fig. 135. The motions of the section S due to flexure in direction AB are transmitted to the indicator Z, moving over a fixed scale M and actuated by the rod Y, bearing with its pointed end in a punch-mark on the column. Flexure is indicated double. In a similar manner the component in direction CD is transmitted by Y to M, hinged to Z_1, which is again hinged to a fixed point, its outer end moving over the arc M at a rate twice that of the flexure. The arcs M are initially adjusted to O, and are provided with positive and negative readings, thus indicating in which quadrant flexure is occurring. Bauschinger uses three of these apparatus; they are very satisfactory.

193. Bauschinger also occasionally used his roller

apparatus, Fig. 42 (77), attaching it as shown by Fig. 136. The motions of the section S are transmitted by means of wires Y and Y_1 to the rollers R and R_1, and indicated by pointers in a ratio of 10 or 20 times actual flexure. The supports for the rollers must of course remain fixed in space.

194. Bauschinger's method may also be readily used for autogrammatic records up to a multiplication of about 5 times, if light wooden bars H and H_1, as shown in Fig. 137, be provided, one carrying a recording-surface, the other H a pencil. The pencil (or pen) will then record direction and magnitude of flexure, and calculations will become unnecessary.

195. The autographic recording-device shown schematically in Fig. 138 is used at the Watertown Arsenal, Boston, Mass., on the Emery machine for flexure during thrust-tests. A bar L, carrying a pen at each end Z and Z_1, is clamped to the strut S, thus tracing lines on T carried by the straining-screws A and B. The flexure of the axis of bar S is derived from these records. However, micrometers are also mounted at points f by which longitudinal crushing is measured.

196. In order to eliminate displacement of the ends of bars, and to confine measurements to those of the axis, Bauschinger constructed an apparatus, plan of which is shown by Fig. 139. Three openable rings R, provided with four set-screws each, are placed about the test-bar S. The two end rings have lugs on which the bar L is carried. The middle ring carries two reading-microscopes M_1 and M_2, one of which reads the vertical deflection on the objective micrometer O_1; the microscope M_2 measures the horizontal deflections on O_2. The bar L is affected but very slightly by the individual motions of end rings, so that its position with relation to the centres of end sections of the test-piece may be considered as immovable. Hence the two components of flexure of test-bar are read directly as referred to the length l_g of bar L. The

measurements are, however, somewhat awkward and require experienced observers.

197. Horizontal machines are generally used for thrust-tests, because they are frequently made to test large bodies, columns, etc., and because vertical machines become inconvenient for long pieces.* Special provision must be made in horizontal machines to freely counterbalance the dead weight of test-pieces, to make accurate tests possible. Bauschinger did this for the Werder machine, supporting the columns by balancing-levers carried by the frame of the machine. Such levers must, however, be so arranged that they offer no constraint to flexure in any direction. Where cranes run above testing.machines this can be done quite readily and most perfectly, as shown by Fig. 140, in which the levers support the column at such points that deflections due to dead load are minima. Fetmajer describes a support by springs. (*L 142*, p. 22.)

198. It is customary to determine the maximum flexure under prescribed test loads, and the permanent set, if any, after release. If the test is to be carried to destruction it is customary to measure flexure due to definite loads up to the limit load, at which continuous flexure or rupture takes place.

If diagrams of flexure due to different loads are desired, absolute measurements of flexure alone are suitable. Within the *P*-limit flexure will be proportional, generally, however, much disturbed by accidental conditions.

d. Torsional Resistance.

1. Definitions.

199. Torsional Resistance, the same as is the case with thrust-resistance, is rarely determined for purposes

* The translator is not of the same opinion as the author, and would limit this statement to machines as at present constructed. A vertical machine properly designed is, in his opinion, much more convenient for this purpose.—G. C. Hg.

of the science of resistance of materials (*L 136*, 1896, p. 1381). When it is, however, done, it is usually a question of testing cylindrical bars, especially of shafts and axles. Testing parts of constructions for determination of torsional resistance is undertaken, but is then no longer a problem for the science of testing. I shall therefore confine myself to giving formulæ for circular sections, and again refer to works on the resistance of materials, such as Bach, Grashof, etc. (*L 137* and *139*), and also to the extensive investigations of Bauschinger (*L 145*) and Bach (*L 138*).

200. A straight cylindrical body is subjected to torsional stress alone when the forces applied produce in all sections but a single moment of force in a plane normal to the axis of the bar.

The torsional moment, M_t, of the couple of forces produces a torsion of the end section 2 with relation to section 1 of the body, Fig. 141. Experience teaches that the end sections, originally plane, remain planes during distortion, and that the amount of torsion is identical in all sections. Hence if the relative distortion of two sections 1 and 2, separated by distance 1, Fig. 142, be the distortion S_u vertical to OA at distance r from axis O, then the torsion of point B at distance r' from the axis will be:

$$S_{t_e}' = S_{e}\frac{r'}{r},$$

or, distortion is proportional to the distance r' from the axis O; its value for various distances r' will be limited by the right line $A'O$. If the torsional stress acting in the sectional plane normal to OA be denoted by S_t, and if the distortion produced by $S_t = 1$ at. (kg/sq. cm) be the factor of distortion S_{t_f}, corresponding to e_f in tension, then

$$S_t' = \frac{S'_{t_e}}{S_{t_f}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad a$$

is the stress at distance r' from axis O.

The factor of distortion S_{t_f} is constant for certain materials under small stress, similar to e_f; for others, such as cast iron, it is variable from the beginning. In the first case S_t is with S_{t_e} proportional to distance from axis O; its value for different r' is limited by the right line $A'O$. In the second case S_t varies according to the same law as S_{t_f}; in this case a curve limits the values of S_t for varying distances from O, instead of the right line $A'O$.

201. The external and internal forces must be in equilibrium in a distorted body, i.e., the torsional moment M_t must equal the moment of distortional stress S_t; hence

$$M_t = \int S_t da r'.$$

As

$$S_t' = \frac{S'_{t_e}}{S_{t_f}} = S_{t_e}\frac{r'}{r} \cdot \frac{1}{S_{t_f}},$$

we shall have:

$$M_t = \frac{S_{t_e}}{r} \int \frac{1}{S_{t_f}} r'^2 da,$$

and for the case of S_{t_f} constant:

$$M_t = \frac{S_{t_e}}{r} \cdot \frac{1}{S_{t_f}} \int r'^2 da.$$

Because $r'^2 = y^2 + z^2$ (Fig. 142), and when

$$\int y^2 da = I_z \quad \text{and} \quad \int z^2 da = I_y,$$

the moments of inertia referred to axes of Z and Y (equal for circular section), we shall have

$$M_t = \frac{S_{t_e}}{r} \frac{1}{S_{t_f}} (I_y + I_z) = S_t \frac{(I_y + I_z)}{r} = S_t \frac{I_p}{r}, \quad . \quad 30$$

in which $(I_y + I_z) = I_p$ is called the polar moment of inertia.

For the circular section we shall have:

$$I_y = I_z = \frac{\pi}{4} r^4;$$

and, correspondingly,

$$M_t = S_t \frac{I_t}{r} = S_t \frac{\pi}{2} r^3.$$

Distortion of section 2 with relation to 1, the small angle ϕ, Fig. 142, is

$$\phi = \frac{S_t}{r},$$

or, from Eq. 30:

$$\phi = \frac{M_t S_{t_f}}{I_y + I_z} = \frac{2 S_{t_f}}{\pi} \cdot \frac{M_t}{r^4}.$$

For a cylinder of length l the relative angle of distortion of end sections will be:

$$\phi_1 = \frac{2 S_{t_f}}{\pi} \cdot \frac{M_t}{r^4} l. \quad . \quad . \quad . \quad . \quad . \quad . \quad 31$$

202. Torsional stresses always appear in pairs vertical to each other (*L 137*, §§ 30, 32). Hence the stress S_t is also vertical to the section in the direction of the axis, and is proportional to its distance therefrom, when S_{t_f} is constant or increases according to the law of S_{t_f} when the latter is variable. The results in different directions of these torsional stresses may be easily seen on bodies of material having different torsional resistance in different directions. Rolled iron, wire, etc., readily show distortion along the fibres during torsion, which often becomes very marked on the piece during winding.

2. The Torsion-test.

203. Torsion test-pieces are to be gripped in such manner by the testing-machine that they are subjected to torsional stress alone. without producing secondary effects; that is

generally by no means an easy matter; hence there are many gripping methods which shall be discussed more fully when describing individual machines.

Cast-iron test-pieces and those of similar material are generally cast specially for test purposes, and hence heads may be readily provided on the cylindrical or prismatic bar which fits the machine available. Bauschinger and Bach used the shapes of bars shown by Figs. 143 and 144, in which the cast square edges were held by blocking in the heads of machines when necessary.

If test-pieces must or can be cut from larger pieces, it is customary to provide square ends of smaller and similar shape, as in Fig. 145. But if such heads cannot be provided, and smooth cylindrical bars must be used (shafts, pipes) as such, it is customary to cut keys and key-seats as in Fig. 146, or the end of shaft is flattened as in Fig. 147. In these two methods rupture easily occurs at the jaws. Occasionally gripping-edges, holding the shafts at the surface, are used, similar to the serrated wedges used in tension-test, which grip more firmly as the torsional moment increases.

204. Distortion is usually measured on a given length of the test-piece l_r, either by indicators moving over graduated circles or by use of mirror apparatus. Indicators may be constructed as in Fig. 148, the graduated arc A being adjusted concentrically about the bar by means of four screws. The pointer Z is then attached in a similar manner at a distance l. The angle of torsion is read off on the graduated arc A. The Bauschinger roller apparatus (*77*, *180*, *193*) may be adapted in a very efficient manner for the same purpose by mounting two of them separated by the distance l as shown by Figs. 149 and 150, the difference in readings between the two giving the angle of torsion; readings of 10- or 20-fold magnitude are thus obtained. Apparatus Fig. 149 operates by a superposed bar; Fig. 150 by a fine wire.

205. Bauschinger used two telescopes for deter-

mination of elastic distortion, which were mounted on hinged rings, provided with four pointed adjusting-screws, and clamped at the proper distance, Fig. 151, taking readings on properly mounted scales. When distance of millimeter scale from centre of bar is $A = 3$ m, then the reading of small angle of torsion

$$\phi = \text{tang}\ \phi = \tfrac{1}{3000}$$

with estimations of $\frac{1}{30000}$. For large angles of torsion the error due to reading on a flat scale must be eliminated by correction (as ϕ is then not $=$ tang ϕ). Besides this, mounting the telescope away from the axis of torsion introduces errors, as shown by Fig. 152, in which $\varDelta a$ would give the error of reading a.

206. The Martens mirror apparatus can also be used for measuring small angles of torsion when mounted as in Fig. 153; when its eccentric position becomes apparent, its readings will also be erroneous, and most defective when mounted in position B'; the distance A will be but half as great for the same multiplication as in the above arrangement by Bauschinger. The advantage in my method is that only the very light mirror, which can be attached with a little speck of wax, is carried by the bar instead of a necessarily heavy telescope. Besides, the telescopes remain mounted on their stand in the usual place, and the effect of the heat of the human body is obviated.

207. Recorders for torsion-tests shall be described later on.

208. In torsion-tests it is customary to measure the distortion due to regular increments of the torsion moment. Thus it is found according to deductions in (*201*) that in case of materials having a constant S_{t_f} there will be S_{t_u} proportional to the S_t, and hence a proportional limit, then a yield-point, a torsion-limit, and finally a maximum load, expressed in terms of S_t and the re-

spective distortions S_{t_e}, referred to the distance 1 between the layers, and the radius $r' = 1$.

The factor of torsion S_{t_f} may be found from S_t and S_{t_e} by Eq. *a* (*200*):

$$S_{t_f} = \frac{S_{t_e}}{S_t}.$$

It bears a relation to the factor of extension, according to the theory of strength of materials (*L 137*, § 31), as:

$$\frac{e_f}{S_{t_f}} = \frac{m}{2(m+1)}, \text{ or in numbers, as } m = 3 \text{ to } 4:$$

$$\frac{e_f}{S_{t_f}} = \frac{3}{8} \text{ to } \frac{4}{10} = 0.375 \text{ to } 0.400.$$

The elastic limit, elastic and permanent distortion, torsional elastic resilience, residuary effects, resiliency, etc., may also be subjects of investigation during the torsion test; but a detailed description of these matters would lead us too far.

209. The law of similarities may also be applied to the torsion-test, and it may be stated that test-bars of symmetrically similar dimensions under equal stress will produce equal deformations, referred to the unit of length.

3. Types of Fractures.

210. A number of typical fractures as obtained with cylinders of low steel (Flusseisen) and cast iron are shown on Pl. 2, Figs. 25, 29 and 30. In cast iron, steel and materials of similar structure the fracture follows a complete revolution of a spiral on the surface, the two ends being joined by a plane passing through the axis of the test-piece. (Compare *203*, Fig. 143, and Plate 2, Figs. 25, 29 and 30.) Bach shows a number of such fractures of cast iron of different sections (*L* 138, 1889, p. 137, Figs. 8–19).

In fine-grained material fracture-lines appear (*122*), usually radiating from a point on the surface at the middle of the helix (Pl. 2, Fig. 25). It may be surmised that the point of radiation in this case was again the origin of rupture. It will be seen that the necessity of more searching comparative study of phenomena of fracture is here again emphasized. I shall give further hints about these phenomena later on.

211. Soft tough metals show fractures (Pl. 2, Fig. 29) which lie almost wholly in a plane normal to the axis, frequently showing slight lumps at the parts near the axis. The fracture has the characteristic appearance of sheared surfaces, but the scales are arranged in spirals, clearly defined, running toward the centre of fracture. It is almost possible to count the number of revolutions made by twisting a wire by following the clearly marked spiral lines on the external surface. It is striking how perfectly irregularities in wire manifest themselves by the preservation of perfectly smooth spots, which certainly play no appreciable part during torsion. (See Pl. 2, Fig. 26.)

I also desire to again call attention to the exhaustive treatment of Torsional Resistance by Bach (*L 137*), and also particularly to the representation of distortion by net lines scribed on bodies of various shapes.

e. Shearing-strength.

212. Shearing-strength of materials is frequently determined, hence the relative conditions should be here examined. In fact, attempts to introduce the shearing-test as a method of testing and to prove its equal utility to the tension-test are not wanting. Kick proposed the application of shearing-test for determination of hardness of materials previous to 1890 (*L 147*, 148).

Alfred E. Hunt also made a proposition in 1893 (*L 147*). But he admitted in 1894 that the results of his investigations were too indefinite to be of any practical value. Ch. Fremont (*L 256*) in 1897, however, developed a very satisfactory autographic

recorder for punching- and shearing-tests, from the records of which he seems to have derived practical results of considerable value, and particular attention is called to his work.—G. C. Hg.

The shearing-test is habitually made by two methods, either as an actual shearing-test or as punching-test.

1. Shearing.

213. Shearing, S_S, is the resistance offered by particles of material against displacement in a plane. Taken strictly, torsional strength, S_t (*200*), should be synonymous with shearing-strength, when the distance between the two cross-sections, relatively distorted, becomes very small. Actually, however, the torsional strength of material is never measured by the shearing-test, because there are always series of secondary conditions which prevent the manifestation of the torsional strength.

2. Shearing-test.

214. In its simplest form the shearing-test is arranged as in Fig. 154, in such manner that shear-blades SS cut the body A with force P on line $\overline{OO}$; i.e., tend to displace the one half A relatively toward the other A on the line $\overline{OO}$. Assuming the shearing-force P as uniformly distributed over the section a, we shall have the shearing-stress $S_S = \frac{P}{a}$. At first glance it might appear that the test would determine actual shearing-resistance; this is, however, not the case, as the following consideration will show. Actual shearing-stress can only be induced at the beginning of the test, at the moment in which both shear-blades just touch the bar. As this contact takes place on a single line, only under the most favorable conditions, further progress must cause immediate passage of the crushing-limit. The material flows laterally until the bearing-surfaces under the shearing-edges have become so large that the force P does not cause further lateral flow. Then, however, the direction of the forces P no longer coincides with the

line $\overline{OO}$. The forces pass as a resultant through a point below the shearing-edges in contact with the bearing-surfaces, Fig. 155, and produce a right-hand moment, so that there will be a bending-stress in addition to the shearing-stress, which is, however, small as compared with the latter. The right-hand moment is in equilibrium with a left-hand moment, the forces L of which are produced by the bearing of the test-piece against the flanks of the shears. The forces L generate friction on these surfaces, to overcome which a part, although small, of P is lost. Briefly, it will be seen that the results of shearing-tests will not determine the shearing-strength accurately.

215. If the body to be sheared is soft and yielding, as wood, lead, leather, etc., a further crushing of the material will become evident in addition to the local crushing under the shear-blades, which makes the procedure much more complex than previously described, so that there may in fact be doubt as to whether the original thickness, or the actual thickness at the moment of beginning of shearing, should be used in calculation of shearing-strength from $S_S = \frac{P}{a}$, in which a = length × thickness.

a. Theoretical considerations generally show that a certain relation exists between S and S_S, but the assumption of properties of materials and of distribution of stress made therein very rarely exists. For wrought iron and steel the ratio between shearing-strength S_{S_M} and tenacity S_M is commonly stated as = 0.7 to 0.8; for cast-iron it may be found even greater than 1.0 (*165, a*). Tests of material having a structure which causes development of different resistance in different directions in the body may even give more manifold results. Tensile strength, as well as shearing-strength, may in this case be very different in different directions, and these conditions are very different in woods. Therefore tests of properties of wood should not be limited to its crushing-strength alone, which is the most readily determined, but the shearing-test at least should also be made.

b. It is, however, easily forgotten that similar matters may become effective in the case of metals as well. Therefore some average values of shearing-

strength of plate iron determined from Bauschinger's tests shall be here given.

These tests published as early as 1874 (*L 2*, Part 2) were intended to determine the changes produced in sheets of exploded boilers. The test-strips were tested in tension parallel and transversely to the direction of rolling, and under shear in three principal directions, as indicated in Fig. 156, $\overline{01}$, $\overline{02}$ and $\overline{03}$. Direction $\overline{01}$ was that of rolling. Sections were made in the planes *A*, *B* and *C*, of which the latter is the rolled surface. Table 21 contains averages of results found with plate of different kinds.

Table 21. **Shearing-tests of Boiler-plate by Bauschinger.**

Kind of Plate.	Shearing-strength S_{S_M} in at. Plane of Section and Direction (Fig. 156).						Tenacity S_M in at. in direction.		Ratios S_S/S.			
	A_2	A_3	B_3	B_1	C_1	C_2	1	2	A_2	A_3	B_3	B_1
a) Puddled Plate	3160	2780	2590	3080	1570	1580	2630	2480	1.20	1.06	1.04	1 24
b) Low Moor "	3210	2830	2680	3190	1480	1420	3200	2800	1.00	1.13	0.96	1.14
c) Charcoal "	2900	2760	2550	3030	1460	1330	3300	2540	0.88	0.84	1.00	1.19
d) Boiler "	3150	2830	2690	3230	1480	1370	3590	2880	0.88	0.79	0.93	1.12
e) Rolled Iron "	3590	3440	2840	3060	1780	1770	4160	—	0.86	0 83	—	—
f) Bessemer "	4390	3980	3920	4460	3780	3720	5030	5180	0.87	0.79	0.76	0.86

It will be readily seen how the values of S_{S_M} and of ratio S_S/S vary, and how much lower the shearing-strength parallel to the surface *C* is than in planes *A* and *B*. Tension-tests of rolled plates in direction $\overline{03}$ are very difficult to make.

216. The shearing-test is also made so as to produce two surfaces 1 and 2, Fig. 157. The body is said to be in single shear when tested as in (*215*), and in double shear when as just stated. But this method does not obviate bending-stresses. The division of forces may be imagined to occur as in Fig. 158. Hence bending-moments must be produced the value of which cannot be accurately calculated, because the distribution of force over parts *a* and *b* is not known, hence the leverage of forces cannot be found. Accurate calculation would also require a knowledge of the friction on the bearing-surfaces, and their influence on distribution of stress.

If it be arbitrarily assumed, neglecting friction, that forces are uniformly distributed over *a* and *b* (actually conditions are

more favorable), the bending-moment will be found according to Fig. 159 (body considered fixed at centre):

$$M = \frac{P}{2}\left(\frac{a}{b} + \frac{b}{2}\right) - \frac{P}{2}\frac{b}{4} = \frac{P}{4}\left(a + \frac{b}{2}\right).$$

This moment is sometimes sufficient to produce rupture by itself.

a. Bach (*L 137*, § 40) made the following shearing-tests with cylindrical bars of cast iron of 0.8 in. (2.0 cm) diam., arranged as in Fig. 157:

No. 1. $P = 6610$ lbs. (3000 kg), bar ruptured by bending in part *b*. Test continued, and shearing occurs actually at 22,490 lbs. (10,200 kg).
No. 2. $P = 6220$ lbs. (2825 kg), bar ruptured as before; shearing occurs at 21,940 lbs. (9950 kg).
No. 3. $P = 7380$ lbs. (3350 kg), bar ruptured; shearing at 22,860 lbs. (10,370 kg).

Because of double-shear load, and the usual assumption that the load P is transmitted equally to the two sheared surfaces (which is by no means correct, however), the shearing-strength of the iron used in Bach's tests was:

$$S_{S_M} = \frac{P}{2f} \text{ for test.}$$

No. 1. $S_{S_M} = \left(\frac{10200}{2 \times 3.14} = 1624 \text{ at.}\right) = 23870$ lbs. per sq. in.

No. 2. $S_{S_M} = \left(\frac{9950}{2 \times 3.14} = 1584 \text{ at.}\right) = 23280$ " " "

No. 3. $S_{S_M} = \left(\frac{1037}{2 \times 3.14} = 1651 \text{ at.}\right) = 24270$ " " "

Average .... 1620 at. = 23810 lbs. per sq. in.

If, from the measurements of Bach's's apparatus (Fig. 159),

$a = 0.88$ in. (2.2 cm) and $b = 1.2$ in. (3.0 cm),

and from $\frac{I}{e} = \frac{\pi}{32}2^3 = 0.785$, and from the above equation

$$M = \frac{P}{4}\left(a + \frac{b}{2}\right),$$

as also from Eq. 17 (*170*), using b_1 instead of η, the maximum tension-load be calculated, we shall have

$$S'_M = M\frac{b_1}{I} = \frac{P}{4}\left(a + \frac{b}{2}\right) \cdot \frac{1}{0.785} = P\frac{2.2 + 1.5}{4 \cdot 0.785} = P \cdot 1.18.$$

Maximum bending-stress in extreme tension-fibre will therefore be in test:

No. 1. $S'_M = 52020$ lbs. per sq. in. ($3000 \cdot 1.18 = 3540$ at.)
No. 2. $S'_M = 49010$ " " " ($2825 \cdot 1.18 = 3334$ at.)
No. 3. $S'_M = 58130$ " " " ($3350 \cdot 1.18 = 3953$ at.)

or an average $S'_M = 53060$ lbs. per sq. in. $= 3609$ at.

From tension-tests of the same bars Bach found:

No. 1. $S_M = 22930$ lbs. per sq. in. (1560 at.)
No. 2. $S_M = 23310$ " " " (1586 at.)
No. 3. $S_M = 24110$ " " " (1640 at.)

or average $S_M = 23450$ lbs. per sq. in. (1595 at.)

Bach's tests on the relation of transverse strength of cast iron upon section (*L 137*, § 22, and *L 138*, 1888, 89) showed that the transverse strength on the tension side of cylindrical bars may be determined from their tenacity as follows:

$$S'_M = 2.12 S_M;$$

using this in calculations, in connection with the average value of S_M, we shall have:

$$S'_M = 56000 \text{ lbs. per sq. in. } (1595 \cdot 2.12 = 3381 \text{ at.}),$$

which approximates the average found from bending-tests $S'_M =$ 53060 lbs. per sq. in. (3609 at.) with sufficient accuracy, as the lever-arms for the bending-moments had certainly been assumed too large, and as the friction of bearings had been neglected.

The ratio between shearing-strength S_{S_M} and the tenacity is formed from the results of tests, as:

$$\frac{S_{S_M}}{S_M} = \frac{1620}{1595} = 1.02.$$

In these comparisons it must not be forgotten that the structure often plays an essential part. This is easily possible in the case of

test-pieces of cast iron, when the latter is of the kind which is apt to chill. In this case the network of white iron near the surfaces becomes more dense, and this may occur to a considerable degree without becoming very apparent, so that the irregular condition of structure may remain even after turning off the skin.

That the ratio between tenacity and shearing-strength is largely dependent upon the peculiarity of materials is strikingly illustrated by Fig. 160, which shows the dependence of tenacity, crushing- and shearing-strength on the amount of nickel contained in an alloy of nickel and iron. All tests of similar kind were always made on similar bars of equal dimensions.

b. From the example given in the previous section it will be apparent that the influence of bending-stress in double shear certainly depends upon the relation between thickness of shear-blades and of the test-piece. For as the bearing-surfaces, hence a and b, become smaller, the lever-arms of the bending-moments will also decrease If it is desirable to adapt the shearing-apparatus to any particular material, and to arrange it in such a manner as to produce a minimum bending-moment, the following method may be adopted:

Assuming tha tforces P and $P/2$ are uniformly distributed over lengths a and b, Fig. 159, and also that the pressure exerted by cheeks a and b on the circumference of the cylindrical test-piece is also uniformly distributed over the projection of the pressure-surface, we shall have crushing-stress under the cheeks:

$$a)\ p_l = \frac{P}{2ad} \text{ and}$$

$$b)\ p'_l = \frac{P}{bd} \text{ when}$$

d = diam. of test-piece.

The pressure $p_l = p'_l$ may be raised almost to the maximum resistance of the material, because deformations of brittle material are very slight up to rupture, and because the concavity of shear-blades will be completely filled in case of tough and ductile materials, after the yield-point has been passed, and because the crushing-strength is enhanced under these conditions beyond that found from unconstrained test-pieces. The shear-blades are of course always made of the hardest and strongest material available. Hence if the maximum value of $p_l = p'_l = S_{-M}$ be assumed as equal to the crushing-strength determined from a free cube of the material, we shall have

$$P = 2adS_{-M} = bdS_{-M}; \quad a = \frac{b}{2}.$$

The shearing-strength of the test-piece is, however,

$$S_{S_M} = \frac{P}{2d^2\frac{\pi}{4}},$$

and from this we have

$$P = 2d^2\frac{\pi}{4} S_S = bdS_{-M} \text{ or}$$

$$b = 2a = \frac{\pi}{2}d\frac{S_S}{S_{-M}} = 1.57\,d\frac{S_S}{S_{-M}}.$$

For the above-mentioned tests of cast-iron $d = 0.8$ (2.0 cm), $S_M = 23810$ lbs. per sq. in. (1620 at.), and S_{-M} may be put at 110,250 lbs. per sq. in. (7500 at.). Hence we might make, under above assumptions,

$$b = 2a = 1.57 \cdot 2 \cdot \frac{1620}{7500} = 0.68 \text{ cm } (.265 \text{ in.}).$$

Bach's apparatus had dimensions of $a = 0.88$ in. (2.2 cm) and $b = 1.2$ in. (3.0 cm). If the bending-stress be calculated according to previous principles, we shall find when using the narrower shear-blades, from the average force required in double shear, § *a*,

$$P = 22430 \text{ lbs. } [(10200 + 9950 + 10370)\tfrac{1}{3} = 10173 \text{ kg}],$$

and from the previously determined dimensions:

$$S'_M = M\frac{b_1}{I} = \frac{P}{4}\left(a + \frac{b}{2}\right) \cdot \frac{1}{0.785} =$$

$$S'_M = \frac{10173}{4} \cdot \frac{0.34 + 0.34}{0.785} = 2203 \text{ at.} = 32380 \text{ lbs. per sq. in.}$$

Hence rupture would not have occurred by bending.

c. An apparatus for making shearing-tests, designed by myself, is used at the Charlottenburg Laboratory (Fig. 161) (*L 149*), in which the thickness of shear-blades equals that of the test-pieces. The apparatus consists of an iron casting in two parts, between which a neatly fitting plunger slides. The shear-blades are hardened and ground steel rings which are either fitted directly or by means of bushings in the blocks and the plunger in such manner that the middle shear-blade may move neatly between the side blades by means of the plunger. The two hollow nuts of the cast frame serve to adjust the side shear-blades by hand, so that they just touch the middle blade without material friction. Fig. 161 is $\frac{1}{4}$ nat. size. The apparatus has bushings for test-pieces of 0.936 in. (24

mm); 0.858 in. (22 mm); 0.741 in. (19 mm); 0.585 in. (15 mm); and 0.351 in. (9 mm) diam.; it is placed in the testing-machine as for the crushing-test, and is very convenient for vertical machines. I have also used it occasionally for shearing-tests under the impact machine.

3. The Punching-test.

217. The procedure of punching is similar to that of shearing, only that a cylindrical surface is cut instead of a plane.

The test is generally made by placing a lamellar test-piece A on a matrix or die M, Fig. 162, of hardened steel. Then the punch S of hardened steel shears out a cylinder of diameter d and length l under effect of the force P.

The punching-strength, i.e., resistance to punching, is

$$S_p = \frac{P}{a},$$

when $a = \pi dl$, the area of surface cut, under the assumption that force P is uniformly distributed over it. Hence for a cylindrical section:

$$S_p = \frac{P}{\pi dl}.$$

For thin test-pieces, in which l is small as compared with d, the punching-strength will be very nearly equal to shearing-strength; for thick pieces, however, the procedure is very complicated.

a. An idea of distribution of stress during punching may be obtained if it be assumed that a thick cylindrical block of lead is to be punched in the direction of its axis, Fig. 163. As long as the force P is not sufficient to produce shearing of the cylindrical section indicated by dotted lines, the material will flow under the punch S laterally and upward, and then mostly in the direction in which there is least resistance, as shown by dotted lines in Fig. 163. It will be observed that the friction on the surfaces of punch and die becomes apparent, and that it bulges more close to the punch than at some distance from it, because the stresses in the body act-

ing radially (especially in one that is elastic) decrease with increasing distance from the axis, and finally effect no further radial flow. If the exterior diameter of the supposed lead cylinder be very large, flow will only be possible into the opening in the die and as upward bulging, because lead is a body of density = 1, and hence the volume of the original body must be equal to that of the body after partial penetration by the punch. Penetration may occur to a noticeable extent only after the crushing-limit (determined from the cube) has been exceeded materially, because free flow of the material is prevented in this case, hence producing in a certain manner the conditions discussed in (*25*). If the stress at crushing-limit of the test-piece assumed is S_{-Y} under this method of loading, appreciable flow can take place only when $P > d^2\frac{\pi}{4} \cdot S_{-Y}$. Shearing of the cylinder, however, can only occur when the height x has been decreased to such an extent that $S_t d\pi x < P$. From this consideration it will be easily seen that the exterior shape of the test-piece to be punched must exert an influence on the results of tests when the thickness of the material surrounding the hole is not sufficient to prevent lateral flow. Hence secondary stresses cannot be prevented in punching-tests, and punching is not a simple process.

b. But as the punching process, superficially examined, appears simple, propositions to use it regularly for purposes of inspecting material were not wanting. About such a proposition, made by Alfred E. Hunt at the World's Fair Engineering Congress, in Chicago, 1893 (*L 146*), I said in an unpublished report: "Hunt started from the erroneous assumption that shearing-strength might be used in a simple manner to deduce therefrom the tenacity of low steel (Flusseisen), and therefore recommended the adoption of shearing-tests to replace tension-tests, under the claim of simplicity of execution, small cost of testing-machine, and of preparation of test-pieces."

"It cannot be denied that this proposition is very seductive, for it is thus possible to construct a portable autographic apparatus operated by a hand-pump, as shown in general by Fig. 164. The piston K forces the punch S through the test-piece P; M is an interchangeable die. The pressure in cylinder C is recorded by an indicator on a paper drum, the latter being at the same time revolved by the lever H, the roller r, and string S, operated by the piston. Counterweight G returns the piston.

"It is not possible, offhand, to form a definite opinion about Hunt's proposition; the figures given by him are insufficient therefor, and require amplification. (It has escaped me what ultimately came of the proposition.)* Conclusions as to the properties

* In a paper supplementary to that of Hunt, read by T. L. Condron before the Engineers' Club of St. Louis, Mo. (see R. R. Gazette, Aug. 31, 1894), the results of all of the investigations are summarized in

of materials derived from tension-tests are hardly admissible when based on results of the punching-test (see *214*). Above all things, it seems impossible to derive measures of elongation and toughness of material by use of the punching-test."

"It is, however, a different question whether the apparatus might not be suitable when used as a practical check on quality of materials in the shop.* In order to form an opinion on this point the following matters must first be demonstrated:"

"All methods which depend upon the use of cutting-tools, as is the case in the shearing-test, have limits of applicability. They become inapplicable as soon as the hardness of the shears becomes insufficient to permit them to fulfil their functions without deformation. Near this limit, in hard material, there will always be doubt about the possible influence due to the deformation of the tools."

"But there are actually two tools used in the punching-test, the punch and the die, and it is known that the work done in punching is dependent upon the diameter of punch, thickness of material,† and relation of punch- to die-diameter. This relation must, however, be adopted according to the kind and thickness of material to insure greatest economy. Besides these geometrical relations the conditions of cutting-edges of punches and dies must be considered. What effect is produced by the wear of these edges on results with identical material? What effect is produced by greater or less hardness of punches and of dies? These are questions which can only be answered by making multitudinous, many hundreds of tests. It will be seen that the questions cannot be answered offhand. The

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the following language: "Until such a series of tests has been made it seems unwise to present any very elaborate conclusions, and therefore the same will be deferred till such time as will enable a broad statement to be made concerning whether the indications of a definite relation existing between the resistance of steels to punching and the ultimate tensile strength, elongation and reduction can be verified, and a definite specification for punching-strength suggested, or until it can be definitely proven that punching cannot be looked to as a means of determining the fitness of material for structures."

This conclusion, drawn by one of Hunt's assistants who actually made the tests, shows definitely that all of these investigations were without practical results. Since the publication of the above statement no further studies of the subject by these investigators have been reported. —G. C. Hg.

* In this respect it must be stated that the Fremont Apparatus and the Henning Pocket Recorders are very much simpler and more practical, dispensing with hydraulic pressure, and have actually given valuable results when used on punches and shears.—G. C. Hg.

† From their shape, when the hole is close to edges, as in flats, angles, etc.

points mentioned do not, however, suffice to reject all consideratior of the punching-test."

"If it is a question of obtaining an approximate knowledge of the uniformity of material in an individual bridge- or boiler-shop, the punching-test may perhaps render good service if it is possible to sc construct the apparatus that it will give alike results on identical material. It would be a simple practical test of the Hunt apparatus to use it in tests of a number of different grades of plate, then to preserve them, and then, after making from 1000 to 5000 or 10,000 regular tests, to again repeat those of the original plates. This test, in my opinion, would determine the practical utility of the Hunt proposition more accurately than a comparison with the results of tension-tests of the same material, as was done by Hunt. The punching-test cannot replace the tension-test in any case, because it does not secure any information of the behavior of material under tensile, crushing or bending stress."

218. It can easily be demonstrated by cutting or etching test-pieces that bending-stresses are produced by punching heavy plate of wrought iron or of other metals. It will appear to what extent the individual layers and the plug have been bent, Fig. 165, and how they have been forced laterally. Therefore the hole is always somewhat larger than the diameter of the plug.

219. Experience has taught that the work of punching decreases and the hole becomes smoother when the die has a larger diameter, *d*, than the punch. This and the foregoing show that the dimensions of the apparatus also exert an influence on results of the punching-test.

If it is desired to obtain comparable results by the punching and shearing tests it will be necessary to establish definite relations between the dimensions of the test-piece and of the apparatus, and invariably preserve these during tests. Unfortunately but very few tests have as yet been made to elucidate this question.

While referring to the earlier tests of H. Tresca (*L 150, 151, 152*) [made in 1869 et sq.], I here reproduce the results of some practice-tests of my students, which were made with various materials under varying conditions. The results are plotted in diagram Fig. 166, being accurate modifications of

autographic records; only instead of plotting pressure and motion of punch the axes represent punching-stress S_p and actual penetration $- e_f$ referred to thickness of test-piece $= 1$. The irregularities and waves in the curves correspond to the fact that shearing is not always continuous, but sometimes intermittent. All conditions of tests are given in above explanations of the figure, so that I need add but the following.

Groups A and C, Fig. 166, show the effect of speed quite clearly. Increase of speed of test requires greater force.

From group D the facts (previously deduced by Tresca* from his early tests) that lead at first undergoes considerable displacement under the punch, that the thickness of punch-plug is considerably reduced below that of original plate, and that thickness remains the same for same size of punch, regardless of considerable variation of plate thickness, may be deduced.

A general examination of curves in Fig. 166 reveals that in groups A to C stress increases very rapidly at the beginning, and up to the beginning of shearing, at which a maximum is reached, after which there is a more or less rapid decrease depending upon the properties of materials and the ratio $\frac{d_1}{d}$ between die and punch. In tests of soft iron the pressure fell gradually quite to 0, and punching occurred inaudibly. In case of soft copper rupture occurs sooner, before the punch has even advanced a distance $= t$. Rupture occurs more rapidly and more sudden the larger d is as compared with d_1 (lines g and c, Fig. 166); i.e., the work done becomes less as the clearance between punch and die increases. Rupture occurs in brass almost immediately after reaching maximum load, before the punch has descended a distance $= 0.3t$.

The condition of surface of punch affects the result. The

* These tests do not appear entirely reliable, in so far as the diagrams given by Tresca invariably show considerable resistance (even in case of lead) even at the moment of shearing.

following tabulation elucidates the above, and also the effect of ratio $\frac{d_1}{d}$. The results stated were obtained from annealed brass plate of 0.156″ (0.40 cm) thick, and by use of punches of $d = 0.78''$ (2.00 cm) with flat and sphero-concave punches. The dies were of $d_1 = 0.784''$ (2.01 cm), 0.819″ (2.10 cm), and 0.856″ (2.20 cm); and hence ratios $\frac{d_1}{d} = 1.005$, 1.050, and 1.100, while the proportion of $\frac{t}{d} = 0.20$. It was found that:

	$\frac{d_1}{d} =$	1.005	1.050	1.100
a) flat punch	$S_{pM} =$	2830	2770	2570 at.
b) concave punch	$S_{pM} =$	2590	2510	2360 at.
relation for $A_f = 100 =$		92	91	92

and if ratio $\frac{d_1}{d} = 1.005$ be made $= 100$ we shall have the decrease of stress under increasing $\frac{d_1}{d}$:

	$\frac{d_1}{d} =$	1.005	1.050	1.100
a) flat punch	$S_{pM} =$	100	98	91
b) concave punch	$S_{pM} =$	100	97	91

4. Shearing and Law of Similarity.

220. It was found in the previous sections that the dimensions of test-pieces and of the apparatus affected the results of shearing-test. It is therefore necessary to establish standards if uniform and directly comparable values are to be obtained by tests. Unfortunately the laws governing these effects have been investigated but very little. It can, however, be stated offhand that the law of similarity, repeatedly referred to, also applies for shearing and punching.

According to the law of similarity, the forces required for shearing or punching bodies A and A_1, made of identical material and being geometrically similar, will be proportional to the surfaces to be sheared.

In Fig. 167, according to assumption:

$$\frac{b}{b}=\frac{t}{t_1}=\frac{1}{n} \quad \text{and} \quad \frac{a}{a_1}=\frac{1}{n^2}.$$

If S_S is to be $= S_S S_{S_1}$ then must:

$$\frac{P}{a}=S_S=\frac{P_1}{a_1}, \quad \text{or} \quad \frac{P}{P_1}=\frac{a}{a_1}=\frac{1}{n^2}, \quad \text{or, because} \quad \frac{b}{b_1}=\frac{t}{t_1},$$

$$\frac{a}{a_1}=\frac{b}{b_1}\cdot\frac{t}{t_1}=\frac{t^2}{t_1^2} \quad \text{and}$$

$$\frac{P}{P_1}=\frac{t^2}{t_1^2}, \quad \text{or}$$

The forces to be applied are as the squares of the plate thicknesses. It should not, however, be forgotten that $\frac{b}{b_1}$ must $= \frac{1}{n}$. As the same observation may be applied to the punching-test (curvilinear instead of rectilinear shear), the diameter d of punch must bear a certain ratio to thickness t of plate; i.e., Stresses S_p will be identical for the same material and different diameters of punch, d, as long as ratio $\frac{t}{d}$ remains constant.

221. As various conditions—such as external dimensions of test-piece, ratio of die to punch $\frac{d_1}{d}$, shape of end of punch, hardness of punch and die, etc.—have considerable effect on results of test, only such results may be compared directly which have been made by use of apparatus which comply with

the law of similarity. Verification, by actual test, of the degree to which all other conditions of test not enunciated, but contained in the law, may be made to fullfil the requirements, must also be had.

In order to satisfy the requirements of the law of similarity, I constructed the shearing apparatus, previously shown in Fig. 161, for shearing cylindrical bodies. In this the thickness of sheer-blade is always equal to the diameter of the test-piece.

The requirements of the law of similarities are moreover readily complied with by adopting a definite relation of $l : t$ between the length and thickness of the test-piece, in case of rectilinear cut and parallel shearing edges, which are the rule in testing materials. The adoption of a definite relation of $l : t = 5$ or 10 is to be highly recommended for testing materials, or the ratio used is at least to be stated in all reports of results of tests.

222. I have built the apparatus shown in Fig. 168 * for punching-tests, and it has given entire satisfaction at the Charlottenburg Laboratory.

The lower casting A is provided with the hardened steel ring B, which forms the die on which the test-piece is placed. The punch C fits in the plunger D. In order that the punch be accurately concentric with the die, the plunger D is guided by the casting E, which is guided by the two lateral dowel-pins passing through casting A. Besides these there are four bolts by which A and E and the test-piece may be firmly clamped together; this arrangement is, however, but rarely used.

Punch and die are removable. Punches of diameters $d = 0.4$ in. (1.0 cm), 0.6 in. (1.5 cm), 0.8 in. (2.0 cm), 1 in. (2.5 cm), 1.2 in. (3.0 cm), and 1.6 in. (4.0 cm) with flat ends are provided; besides these there are punches with

* The apparatus used by Tresca as early as 1863 is, however, quite similar to this in detail.

convex ends of $R = 2d$ in use. For each punch there are three dies of the following diameters of upper ends of holes:

$$\text{of } d_1 = 1.005d; \ = 1.050d; \text{ and } = 1.100d.$$

If the diameter of punch be selected with relation to thickness of test-piece, the devices provided will permit the use of an almost constant relation d/t as required by the law of similarities.

f. Resistance to Impact.

1. Drop-tests—General Arrangement.

223. The types of tests previously described were always supposed to be carried out by application of steady loading acting very slowly. In machine construction, in railroad service, and on many other occasions there are frequent cases in which the material is subject to forces applied very rapidly, and in fact to impact.

Some materials behave very differently under effect of loads applied steadily or suddenly. Bars of pitch, sealing-wax, glass, etc., may be loaded quite heavily when loads are applied steadily. Pitch and sealing-wax of course rupture under very small loads if long applied; under this condition they are very ductile and tough, but very slight impact suffices to crush them without any noticeable elongation or distortion. The material of a rail may give very satisfactory results when subjected to tension or transverse tests under steadily applied stress, but very unsatisfactory under impact. For this reason it has before this been customary to test rails and other material by impact. Only after the tension-test had been very generally introduced, the drop-test was frequently omitted; latterly it has again been more largely appreciated.

224. Drop-tests are made in so-called impact machines, in which heavy weights, guided by vertical rails, are allowed to drop on the test-piece in such manner as to

produce crushing (bulging), rupture by tension, bending, torsion, shearing, punching, etc. The test is usually made either on specially prepared test-pieces of simple shape, or on parts of structures (axles, tires, rails, etc.).

2. Impact Machines.

225. Tests made on impact machines very soon show that methods of supporting test-pieces, the masses of the apparatus, and many other matters influence the results of tests very appreciably, and that different results may be obtained with different machines under like conditions of tests. Just as it is necessary to calibrate all testing-machines frequently, and to observe definite principles of construction of all apparatus if they are to produce comparable results, this is also the case in impact machines, only to a greater degree. After considerable arbitrariness prevailed in this matter for a long time, the "Conferences for Unification of Standard Methods of Testing" at Dresden in 1886 (*L 128*, p. 9) first laid down principles which should be embodied in every impact machine to insure comparable results. The "Association of German Railway Managers" has essentially adopted these principles for the construction of those impact machines which are to be used for making the prescribed drop-tests during inspection of railway material.

226. As it can be foreseen that the instructions of the "Association of German Railway Managers" will be gradually generally adopted, the fundamental conditions to be fulfilled by an impact machine shall be here given in accordance with these instructions; they shall, however, be supplemented by the resolutions of the above-mentioned conferences. In order to be able to iden-

tify the following directions as to their origin, those adopted by the Railway Managers shall be followed by *R*, while supplements, taken from "Resolutions of Conferences," shall be followed by *C*.

1. The complete design of a standard impact machine is not to be prescribed, but only those parts are to be defined which may influence the results of tests. It is recommended to construct the frame of the machine of iron (low steel) and to erect it under cover. *C*.
2. Standard drop-weight ball is to weigh 2200 lbs. (1000 kg); 1100 lbs. (500 kg) is to be permissible exceptionally. *C*.

   The ball shall weigh from 1320 lbs. (600 kg) to 2200 lbs. (1000 kg) for testing rails, axles and tires, and 440 lbs. (220 kg) for wheel-centres. (1760 lbs. (800 kg) is recommended by others for locomotive axles.) *R*.
3. The ball may consist of cast iron, cast or wrought steel. Its shape is to be such that its centre of gravity be as low as possible. *C*.
4. The axis of the ball must coincide with that of its guides. *R*. *C*.
5. Special marks on the anvil or base are to indicate the axis of machine. *C*.
6. The ratio of length of guide-cheeks to width between guides shall exceed 2 : 1. *C*.
7. The guides are to be made of metal, e.g. rails, and are to be so designed that the ball has but slight play. Lubrication by graphite is recommended. *C*.
8. A special tup of hammered steel is to be fitted concentrically with axis of ball on the anvil, by dovetail and wedge. Special marks shall indicate fulfilment of this requirement. *C*.
9. The surface of striking-block is always to be plane; hence filling-pieces of proper shape, and having an upper flat surface, are to be fitted to the pieces to be

tested, in all such cases as rails, axles, tires, springs, etc. These riders should be as light as possible. *C.*

R e a s o n: The same ball with plane face is to be used in every case, with regard to simplification of devices for the impact machine, and a single rectification of the weight of ball as under 19 and 20. *C.*

10. The hammer-face of tup is to be rounded off to a radius of not less than 6 in. (15.0 cm); in case of tests of tires the tup is to strike upon the centre of a rider made to fit the tire and having a flat upper surface, its weight not to exceed 44 lbs. (20 kg). *R.*

11. When publishing results of tests or writing certificates of acceptance the shape of riders used must be accurately stated. *C.*

12. The release or clevis for the ball shall be constructed in such manner that it does not affect the free fall of the ball. *R.*

    The device shown in Fig. 169 is especially recommended. *C.*

    A device which prevents the accidental release of ball when at any height shall be provided. *R.*

13. The weight of anvil and base shall be at least 10 times that of the ball. *C.*

    The weight of anvil and base shall be at least 10 tons gross. This base shall consist of a single block of cast iron. *R.*

14. The foundation shall be inelastic and a solid masonry monolith, whose dimensions depend upon the space available, *R*, *C*, but the height of which shall be at least 39 in. (1 m). *R.*

15. The bearing-blocks for the test-piece are to be rigidly secured to the anvil by wedges, etc. *C*, *R.*

16. Guards are to be provided which will prevent rails, axles, and tires to leave their bearings after impact, without restraining free motion. Provision must be

made for holding tires in proper position during impact. *R.*

17. Impact machines up to 20 ft. (6 m) drop deserve greater confidence than those of larger drop; it is therefore recommended that new machines do not exceed 20 ft. (6 m) drop. *C.*

18. The vertical scale for reading height of drop of ball shall be movably fixed on the guides, and the moment of impact shall be stated in meter-kilograms ($h \times W =$ height of drop $\times$ weight of ball) [or in foot-pounds in the United States and England]. The height of drop of ball is to be adjusted after every blow to the deflection of test-piece. *R.*

    When using balls of different weights it might be more practical to assume the height in meters (centimeters), because then the same scale may be available in every case. Attention is called to the multiplicity of weights of balls prescribed by *R* under 2.

19. Every standard impact machine is to be calibrated. *C.*

    It is by no means impossible that impact machines constructed with greatest possible care may nevertheless give, for unknown reasons, incorrect effects. Comparable results can alone be obtained when frictional resistances are allowed for or equilibrated. *C.*

20. The following methods may be adopted for determining the effective weight of ball:

    α. A spring-balance of sufficient capacity is attached between the ball and clevis, and the effective weight of ball is read while slowly descending. Thus the weight of ball less the friction, and during ascent the weight of ball plus the friction, are determined.

    β. The weight of ball is determined from its effect during a single blow of definite drop on

a standard copper cylinder placed truly centrally, and made from the best stay-bolt copper, of a definite shape, still to be determined, and of definite weight. *C.*

21. Such standard copper plugs shall also be used for the relative comparison of different impact machines, for calibration. *C.*

(The Royal Testing Laboratory at Charlottenburg furnishes such standard plugs upon application.)

22. Impact machines in which the work of friction between guides and ball exceeds 2% of the work of impact of ball are to be discarded. *C.*

227. Kick (*L 100*, p. 101) used a ballistic impact machine for the purpose of making scientific tests; its construction is fully shown in the reference. Its principle is the following: The ball B and anvil A, Fig. 170, are supported by wires *ac* and *bd* from the ceiling, in such manner that both can pendulate over the graduated arcs *Ma* and *Mb*. The suspension is so arranged that lateral oscillations are precluded, and screw-couplings *e e* permit adjustment of positions of A and B so that both swing in one axial plane. For purposes of test, the test-piece is attached to the anvil, and the ball is withdrawn by a string until a pointer moving with the ball over the scale *Mb* indicates the desired drop. The ball is released by burning the string F, thus causing it to drop without any lateral motion. A part of the work stored in B is absorbed by deformation of the test-piece; another is transferred to the anvil A, in which it produces certain motion which can be read off on scale *Ma*.

228. I constructed several small impact machines for the Charlottenburg Testing Laboratory having balls weighing from 1 lb. to 440 lbs. ($\frac{1}{2}$–200 kg). The smallest of these machines has a guide which consists of a drawn-iron tube in which the ball of steel having an exceedingly hard striking-surface is raised by means of a string, and

then supported in position by a pin inserted in holes in the tube, which when withdrawn permits the ball to drop from the desired height. The small apparatus shown by Fig. 171 was originally intended for comparative tests of hardness of lead shot, but has since been used for many purposes.

229. Another somewhat larger impact machine serves for tests of building-stone, flags, roofing-stone, strawboard, etc. It is equipped with pear-shaped balls, dropping free, weighing from $1\frac{1}{8}$ to 11 lbs. (1–5 kg). The stones are bedded on dry sifted sand; the strawboard is nailed on a wooden frame.

230. An impact machine of about 15 ft. drop, having balls of 44 to 220 lbs. (20–100 kg) weight, has been so constructed that any kind of impact-test can be made with it. It is arranged for tension, transverse, crushing, and indentation-impact tests, and shearing and punching tests can be made with it by use of the devices shown in (*216*) and (*223*), Figs. 161 and 168. The arrangement for making tension-tests* on this impact machine consists in principle of a block B, Fig. 172, which is secured to the anvil A, and is essentially a frame R which glides between the guides of the machine. The test-piece Z is held by the upper end of the block B and by the lower end of frame R by means of split rings, similar to the method shown in (*70*) Fig. 27, for making tension-tests. The ball G strikes the top of frame R, and this transmits the impact to the test-piece, which transmits it by the support B to the anvil A.

231. The following impact-test has lately been prescribed by the German Railway Managers for wheel-centres and low steel disk wheels. The wheel-centres and disk wheels are supported at the rim on wooden blocks horizontally. A bushing composed of four segments, planed on inner faces to a taper of $\frac{1}{20}$, is placed in the hole for the axle. An accurately fitting pyramidal steel plug is then

* A similar device had been previously used by Uchatius (*L 100*).

driven into the tapered hole; in case of a wheel with bore of 5.65 in. (14.5 cm) this is done by 6 blows, in those of 5 in. (13.0 cm) bore by 5 blows, using a 440-lb. (200-kg) ball, delivered from successive drops of ($1\frac{1}{2}$, 2, $2\frac{1}{2}$, 3, $3\frac{1}{2}$ and 4 m) 4.92, 6.56, 8.20, 9.84, 11.48, 13.12 ft. The plugs and bushings are to be well greased and rubbed off dry before test.

232. A fourth impact machine was constructed by me for the Charlottenburg Testing Laboratory for making impact tests of wire ropes which were to be investigated as to the effect of a great number of light blows. In this case the anvil consists of a heavy iron frame A, Fig. 173. The rope Z is suspended from it, and loaded at its lower end by a heavy weight G. The weight carries a gas-pipe F, which serves as a guide for the ball B, which is raised and dropped about 13 times per minute by the machine. Very extensive investigations of strength of ropes and rope connections have been made by means of the apparatus, and the results have been reported by Rudeloff (*L 153*).

233. Rudeloff also provided this machine with a device which served for comparative tests of railway-track ballast, and it answered the purpose admirably. He sifted the gravel and broken stone to definite sizes, then placing them in boxes with fixed or movable sides, and the ball, having the shape of the tamping-tool, was then dropped into the ballast. The standard of comparison used in this case was the quantity and shape of reduced ballast after a definite number of blows. The degree of reduction was determined by repeated sifting.

234. The simplest form of impact machine (drop) is frequently used in foundries for breaking up scrap and sometimes for testing cast iron. For the latter purpose a plate 39 in. (1 m) square, 0.8 in. (2 cm) thick, Fig. 174, is bedded on a bed of uniform sifted moulding-sand, dropping a ball weighing about 55 lbs. (25 kg) from various heights, increasing it 10 in. (25 cm) at each blow. Juengst (*L 154*) tested

cast-iron plates in this manner, the best of which did not show signs of cracking until a drop of $13\frac{1}{8}$ ft. (4 m) was reached, and failed under a drop of $17\frac{1}{4}$ ft. (5.25 m).

235. The previous paragraphs show that the impact machine of simple form is handier and more readily applicable for many kinds of tests, especially for inspecting materials in shop use, and can be made more valuable than the tension-test machine, because it is cheaper, can be handled more readily, requires less costly preparation of test-pieces, and gives results quickly; the method of making the tests can also be readily modified to suit special purposes. For all of these reasons it should be an object to secure more general introduction of the impact-test for testing materials.

3. Upsetting- (or Bulging-) test.

236. The upsetting-test with impact machine corresponds to the crushing-test under steady load with the testing-machine; the test pieces may be of the same shape as in the crushing-test. The difference between the two methods of applying stress consists essentially in the speed of deformation in the first case it is produced very rapidly, in the fraction of a second, in the second case slowly.

In the case of tension-test machine the force applied and the deformations produced thereby can be measured directly, and hence the mechanical work done during deformation may also be measured directly; it is absorbed entirely by the test-piece. The amount measured is therefore the net foot-pounds of work.

In the case of the impact machine, however, a large part of the work stored in the falling ball is lost, and only the total or gross work of the ball $A = hW$, $h =$ height of drop and $W =$ weight of ball, can be determined.

It will be at once observed that the amounts of work done during the two deformations are not directly comparable.

237. The practical execution of impact-tests is, however, as simple as that of crushing-test. A prismatic body, as a

rule a cube or cylinder of length $l =$ diameter d or of proportion $l = 0.886d$, i.e., $\frac{\sqrt{a}}{l} = 1$ [as was found applicable in case of the crushing-test (*167*)] is placed upon the anvil and the ball is dropped upon it. The amount of longitudinal upsetting is measured as in the crushing-test.

238. Thus far it has not yet been attempted to determine the conditions of stress, during deformation by impact, mathematically, a problem which, on account of the complexity of the occurrences, might be exceedingly difficult. It had been considered sufficient to compare the gross work or impact directly with the change of shape produced. This is done best and most comprehensively by diagrams. These can be plotted as representing the entire body, hence the gross impact $A = Wh$ in connection with the shortening or upsetting produced, $-e$, or the specific impact, i.e., the work absorbed by a unit of volume or weight of the test-piece, compared with the unit of length $-e_1 = \frac{-e}{l}$.

Hence when $v =$ volume of body in cubic inches (in ccm) and $w =$ its weight in lbs. (gr), the specific (work of) impact:

$$i = \frac{A}{v} \qquad \text{or} \qquad i_1 = \frac{A}{w}, \quad \text{or}$$

$$i = \frac{hW}{v} \cdot \frac{\text{ft.-lbs.}}{\text{cu. in.}} \qquad \text{or} \qquad i_1 = \frac{hW}{w} \frac{\text{ft.-lbs.}}{\text{lbs.}}.$$

In the following the specific impact shall always be referred to the unit of volume when not otherwise specified. In order to convert this value to unit of weight it should be multiplied by the reciprocal of the volumetric weight $\frac{1}{Wv}$, hence

$$i_1 = \frac{i}{Wv}.$$

According to Fig. 175, the "crushing" will be

$$-e = l - l_1,$$

or the "upsetting":

$$-e_i = \frac{l - l_1}{l} = -\frac{e}{l},$$

or in per cent $$-e_i\% = \left(1 - \frac{l_1}{l}\right)100.$$

The index i shall invariably be used hereafter, in connection with all values relating to impact-test, to distinguish them from those deduced from the crushing-test.

Impact crushing-factor i_f might be applied as in (*34*) to relation between shortening of unit length and unit of work:

$$i_f = \frac{e_i}{i}.$$

239. If a body having a density = 1 be tested, it will not change its volume appreciably during deformation. Hence a relation exists between diameter d_1 (Fig. 175) and the length l_1, which, neglecting the actual bulging, will be expressed by

$$v = v_1, \quad \text{or} \quad \frac{\pi}{4}d^2l = \frac{\pi}{4}d_1^2l_1;$$

ɔr when $d = l = 1, \quad l_1 = \frac{1}{d_1^2};$

ʼhen $l = 0.886d, \quad l_1 = \frac{0.886}{d_1^2}.$

ence in case of dense bodies it suffices to determine the setting as a measure of deformation.

240. If now a diagram of an impact-test be conιcted which is based on these ideas, it must be remem:d that but one point can be plotted for each impact, viz.,

the final condition assumed by the body under this impact. If the test were carried out by applying repeated impact of the same specific work, i.e., several blows of the ball dropped an equal distance, the upsetting produced after each blow would be represented by a series of dots, Fig. 176. A second material tested under similar conditions would produce a second series of points, etc. To obtain a more comprehensive view, these points are then connected by a line of constant curvature (a curve of averages). The distance of the points from line $\overline{O\text{–}i}$ shows the individual upsetting — e_i%, and that of line $\overline{AB}$ the length of body after test expressed in per cent of original length.

241. In order to evolve the laws governing deformations of materials during impact-tests, and to be able to prepare uniform rules for testing materials by impact, I have amplified Kick's tests (*L 100*) to a considerable extent. The results have been published in the "Mittheilungen a. d. Koenigl. techn. Versuchsanstalten zu Berlin," 1891,* and exhaustively discussed.

The laws stated in following paragraphs may be deduced from these tests and those of Kick.

a. Effect of Speed.

242. The work done by the ball is equal to weight times drop. If like deformations were produced by like work of impact, it would be immaterial whether the impact be produced by large weight and small drop, or by a small weight and large drop. In the first case the speed obtained by the ball at instant of impact is less than in the latter; i.e., the speed of deformation is smaller than in the latter. Actual test will readily decide whether this difference in speed has an influence on deformations which becomes practically noticeable; actually, it certainly exists.

* Reports of the Royal Techn. Testing Laboratories at Berlin, 1891.

Kick demonstrated by his tests that the velocity of impact between wide limits does not noticeably affect results in case of certain materials, for he found in lead $d = l =$ 0.59 in. under an impact of 12.5 ft.-lbs. (1.77 cm kg) or for $v = 0.16$ cu. in. (2.7 ccm) and $i = 78.1 \frac{\text{ft.-lbs.}}{\text{in.}} \left(66 \frac{\text{cm kg}}{\text{ccm}}\right)$ the following crushing:

Impact.	1	2	3
a. Height of drop h = 10 ft. (307 cm); weight of ball w = 1.25 lbs (0.576 kg)	19.3	35.0	47.0%
b. Height of drop h = 0.85 ft. (26.1 cm); weight of ball w = 14.75 lbs. (6.75 kg)	19.8	34.4	46.3%

The velocity at impact, according to the common laws of gravity, will be 25.4 ft. (7.75 m) and 7.2 ft. per sec. (2.2 m) or

$$v_a : v_b = 3.5 : 1.$$

Under similar conditions for other lead cylinders $d = l =$ 0.7 in. (1.8 cm), and for $i = 46.5 \frac{\text{ft.-lbs.}}{v}$ he found:

Impact.	1	2	3	4
a. Drop h = 10 ft. (307 cm); v = 25.4 ft. (7.75 m)	15.1	25.6	34.8	41.8%
b. Drop h = 0.85 ft. (26.1 cm); v = 7.2 ft. (2.22 m)	15.1	26.5	35.9	44.4%

Therefore the effect of striking velocity does not appear to be great, although these tests of lead and small specific impact cannot be considered as conclusive.

b. Upsetting- (Bulging-) test and Law of Similarity.

243. According to the law of similarity:

like specific impact should produce like upsetting of bodies of like material geometrically similar (see *277–281*).

To test this law series of tests of so-called standard plugs (cylinders) having $d = l$, of various dimensions, were tested under regularly decreasing specific impact. For this purpose I used rolled brass and copper plugs having $d = l = 0.4$ in. (1.0 cm), .507 in. (1 3 cm), 0.6 in. (1.5 cm), which were subjected to specific impact varying from $i = 60$ to 650 cm kg/ccm for each blow. The upsetting $e_i\%$ produced is plotted in curves Fig. 177.

a. The diagrams of upsetting-tests shown in the "Mittheilungen" (*L 155*) have been plotted on a different plan from that adopted here. In the former case the sums of the specific impacts e_i and final lengths $100 - e_i\%$ are correlated, while in the latter the upsetting $e_1\%$ is used; the results there given must hence also be modified in this sense. Comparisons are nevertheless easily made.

In this connection the combination of tension and crushing diagrams as previously used in (*56*), Fig. 13, drawn in the first and third quadrants, shall be used for impact-, tension-, and crushing-tests as well. For this reason the curves for upsetting test are drawn as in Fig. 176 in the third quadrant.

b. The adoption of a definite method of illustration, and, as shall be shown directly, of a definite selection of relation of ordinates, if indeed not of scales to be used, offers such extraordinary advantages for demonstration and comprehensiveness of the results of tests to be represented, that it does not appear to me as an idle pastime to now dwell upon this matter at greater length than has been done heretofore.

The value of plotting diagrams having ordinates representing stress and deformation of the unit of length has been repeatedly referred to (*40*, *185*). Geometrically similar bodies of identical material produce coincident curves when using the same scales while plotting. This method affords the best means for exact comparison. Hence there is a

standing order in the Charlottenburg Laboratory to invariably use the same scale whenever this is possible. All diagrams are plotted on cross-section paper of 2.0×2.0 cm, the squares divided in 10 spaces (0.8 in. $\times$ 0.8 in.). [In the United States and England the paper of 1 in. and $\frac{1}{10}$-in. cross-lines would be most suitable and is commonly used.—G. C. Hg.] The sheet is 8 in. $\times$ 7 in. (20×18 cm), which is a very convenient size, with ample margin. Exceptionally two such sheets are glued together. Students must also conform to the same rule. The scales used are as a rule so chosen that 2 cm for $S = 1000$ at., or for e_1 or $\frac{e\%}{l_g} = 0.1$, or for $e\% = 10\%$; this proportion of ordinates of stress and deformations is retained as nearly as possible when different scales of diagrams are used, and half or twice this ratio is used only in case of very strong or of very weak materials. If it is desirable to represent peculiarities of deformations on a different scale in a more pronounced manner, multiples of the original are used as much as possible. If these rules are observed, presentable diagrams will also be available for occasional publications, as photographic reduction to standard dimensions, without disturbing ratio of ordinates, is possible. It will no doubt be readily seen that the general introduction of this proposition would be of some value, when diagrams found in literature and habitually given, as those, e.g., of low steel, are recalled to mind. In Fig. 179 are shown two extreme diagrams of identical material.

c. The development of principles of graphical representations of results of tests may indeed be carried much further, and in order to preserve uniformity in this work the plan shown in Fig. 180 shall be followed throughout. Ordinates in direction of Y shall represent stress S, S_t, and specific resiliency A_f, while abscissæ in direction X shall represent deformations e_1, $e\%$, $\frac{e\%}{l_g}$; if volumetric representation

(e.g., influence of chemical composition, amount of work, heat, time, etc.) comes in question, the direction Z is available. The body shown by broken lines in Fig. 180 indicates a volumetric representation of the relation of tension and crushing-resistance and a third property. In this case valid reasons for representation of crushing in the third quadrant necessitated the adoption of negative representation of the law of deformation during crushing.

d. In order to show the results obtainable by this method of representation, Figs. 181 to 183, being photographic reproductions of some of the models in the Museum of the Charlottenburg Laboratory, showing properties of materials, are here given.

Fig. 181 represents the variation of tenacity of Martin steel caused by increasing carbon contents Fig. 182, the variation of bending-resistance of similar material caused by increasing manganese contents. Fig. 183 represents the law of variation of elongation due to increment of stress $\Delta S =$ 100 at. of hard-drawn copper wire under the annealing effect of temperatures varying from 0–500° C.; the sudden transition from hard to soft condition during annealing at a temperature beween 300° and 400° C. is beautifully shown.

Besides representing the relation of properties of materials to peculiar conditions by glyptic models (wood, plaster, etc.), I have frequently used pins with colored glass heads to represent results of official tests of paper, thus obtaining striking results. The three ordinates represent rupture lengths, elongation, and resistance to crumpling and friction, measured by length of needles, and composition by the color of heads. Threads stretched over the needles indicate boundaries between different classes of paper.

Laws which can be represented by lines in space may be illustrated by differently colored bent wires; colored threads are also used especially to represent intersecting planes, but they are unpractical because they are dust-collectors, become slack under hygroscopic changes, and for other reasons.

Drawing colored lines and surfaces on consecutive glass plates, and even curving glass plates to the surface of plaster models, have been tried by other authors for different purposes.

244. The curves drawn in Fig. 177 have been used in Figs. 184–187 to more clearly illustrate the relation between upsetting and the specific impact of individual blows. For this purpose plane sections at intervals representing 10% of e_i% have been passed through the ideal body produced by arranging diagrams of Fig. 177 of individual groups consecutively, in such manner that the distance between individual lines from the O-plane (XY, Fig. 180) is proportional to the specific impact for each blow. These sections would be parallel to the YZ-plane, Fig. 180. Fig. 184 shows such a group of sections for bodies $l = d =$ 0.6 in. (1.5 cm) of rolled brass, struck by the ball I; hence it gives lines of equal upsetting. It must be plain from the entire procedure of the impact-test that these lines can only serves as auxiliaries, for, as fractions of blows cannot be given, only certain points of these curves correspond to actuality, and all of these must lie on the lines 1 to n radiating from the point O. These rays indicate the number of blows. By means of such a plan as given in Fig. 184 it is possible to determine how many blows, and the specific impact of each blow, required to be applied to produce a given upsetting of the material under consideration.

245. Curves of identical upsetting of bodies of rolled brass of $l = d = 0.6$ in. (1.5 cm), 0.507 in. (1.3 cm), 0.4 in. (1.0 cm), derived from curves in Fig. 177, are plotted superposed in Fig. 185. The full lines refer to plug of $d = 0.6$ in.; the broken line to that of $d = 0.507$ in.; and the dotted line to that of 0.4 in. diameter. It will be seen from these lines that the same amount of upsetting will be produced either by one heavy blow, i.e., one of great specific impact, or by several light blows, i.e., each of small specific impact; but the sum of the specific impact of all lighter blows is greater than that of the heavy blow.

Under identical total impact heavy blows produce greater upsetting than light blows.

246. If the law of similarity previously enunciated were strictly met, the three groups of curves in Fig. 185 for $d = 0.6$ in., 0.507 in., and 0.4 in. would coincide. It will be seen that this is nearly the case in the groups for $-\epsilon_1\% =$ 10, 20, and 30%, and more nearly so as the specific impact of each blow is greater.

The deviations from this law, which may be assumed to be generally strictly correct, may be laid to the apparent effect of secondary conditions of tests. As previously stated in (*236*), a part of the impact of the ball is invariably lost, and this portion is variable. It depends upon the magnitude of the impact, the striking velocity of ball, and upon the properties of the material tested, and these vary with the amount of deformation. This can be readily perceived by noting the behavior of the ball immediately after impact. In tests of lead the ball remains almost dead or at rest. With soft copper it remains dead at first, but begins to dance after a few blows. Lead remains soft and inelastic; copper grows harder and more and more elastic.

247. The law of similarity holds good for the entire test; it may therefore be extended up to the instant of rupture (*L 100*). Hence it may be said that under similar conditions rupture is produced in geometrically similar bodies of identical material by identical amounts of specific impact. Therefore this sum or amount of specific impact which is just sufficient to produce rupture may serve as a measure of quality of materials. If with Kick (*L 100*) the specific impact of a single blow which produces rupture be called the factor of rupture (Bruchfaktor) of the material, it may be said that it is a characteristic constant for the material and the standard shape of test-piece. In those materials which are not ruptured under impact it would be best to substitute that specific impact which produces a definite amount of crushing of the stand-

ard test-piece, e.g., $-e\% = 80\%$. I desire to propose the name of "Crushing-factor" (Stauchfaktor) for this conception, but to include in it the factor of rupture, for sake of simplicity. Hence the crushing-factor is that specific impact in ft.-lbs. (cm kg/ccm) which when applied to a body of fundamental shape (sphere, cube, standard plug, etc.) in a single blow will either just produce rupture or crushing $-e\% = 80\%$.

The manner and shape of fracture are also subject to the law of similarity (*L 100*), as previous discussion has probably shown, and will be confirmed presently.

c. Influence of Shape of Test-piece.

248. Upsetting-tests will probably be used solely for purposes of testing materials; the problem of testing structural detail by this test will hardly ever arise. This case has thus far occurred but a single time at the Charlottenburg Testing Laboratory (*L 155*), when it was a question of determining the impact permissible in driving iron tubes as sheet-piling without injury to the tubes.

There is seldom any reason for using any but the simplest prismatic shapes when testing materials, and as a rule recourse would be had to use of cubes or cylinders of $l = d$, or, as in crushing-test, to cylinders of length $l = \sqrt{a} = 0.886d$. The first two shall here again be called standard, the latter proportional, test-pieces.

It may sometimes be necessary to investigate tubular prismatic bodies by impact; it rendered very good services at the Charlottenburg Testing Laboratory in case of comparative tests of Mannesmann and other tubes.

249. Although the three shapes prescribed are to be generally used, it will nevertheless be necessary to determine the possible effect of deviations from these

standard shapes on results of upsetting-test. Practically errors in length-ratio are of the first importance in case of cylindrical plugs.

In order to determine this I made several series of tests of cylinders of copper and rolled brass in which the diameter $d = 0.6$ in. was constant, but the length varied from 0.08 in. (0.2 cm) to 1 in. (2.5 cm). All bodies were then tested under identical impact, i.e., under equal drop of the same ball; they were therefore tested under different specific impact, depending on different volume. The results are plotted in Fig. 186 for copper and in 187 for rolled brass.* In the diagrams dotted lines of equal upsetting of standard plugs of identical material obtained under varying impact are plotted above the full lines, showing identical upsetting with different lengths.

The two curved surfaces conceived as passing through the groups of curves representing the laws of deformation, drawn full and dotted, must intersect, and the trace of both surfaces is indicated in Figs. 186 and 187 by the fine broken-dotted lines; they should in both series of tests be represented by a figure corresponding with the standard plug $d = l = 0.6$ in., which is the case with sufficient approximation when it is considered that the test-plugs used for comparison had not been cut from the same bar. The ideal curved surfaces of each figure, in addition to their common trace, must also contain the right lines through O (lines Y and Z, Fig. 180) in common. For it is a fact that for every body, of whatsoever kind of material, no impact of any magnitude, nor any number of blows of impact = 0, can produce any deformation of the test-piece. The lines l connecting the small circles indicate the lengths l tested.

The two groups of curves in Figs. 186 and 187 show that slight variations of prescribed length $l = d$ do not make themselves as much felt during

* Complete explanations and values are to be found in the reference (*L 155*).

the first blows, i.e., during small degrees of upsetting, as during greater upsetting.

d. Influence of End-surfaces.

250. As deformation during upsetting-tests is very similar to that during crushing-test, it is apparent that the influence of end-surfaces must also be similar to that found in crushing-tests.

In order to obtain a knowledge of its degree I made tests with standard plugs the end-surfaces of which were rough, smooth, or oiled. The influence of friction was made undoubtedly apparent by these tests, for the upsetting was greater in case of test-pieces with lubricated ends than that of those which were rough.

I do not here publish the data found (*L 155*, p. 26), because they should be still further amplified.

e. Measurement of Elastic Upsetting.

251. As it is interesting to know the amount of elastic deformation during upsetting, it was attempted to determine the elastic and permanent deformations of cubes of cast iron (*L 155*). These tests also require amplification. I shall therefore confine myself to a description of the method adopted.

As previously indicated (*246*), lead shows exceedingly slight elasticity during impact-tests; it is not absolutely inelastic, for lead objects, e.g., tuning-forks, produce a tone, although very much deadened.

If now a lead wire be attached to the body to be tested for elastic behavior, so that its end-surfaces are flush with those of the test-piece, and the test be then made, the elastic body will be shortened more by the blow than the amount indicated by the measurement l_1 after test; because of its elasticity the body again extends, while the lead wire retains the length given it by impact. The difference be-

tween the lengths of the two bodies gives the elastic deformation of the test-piece.

252. I shall add briefly that an approximate measure of impact producing elastic deformation, absorbed by the test-piece and the mass of the impact machine during each blow, hence that amount which is lost during production of permanent deformation of test-piece, can be determined. This can be done by measuring the height of recoil of the ball after impact. It can easily be proven that this resilience is not due to the test-piece alone, by testing two equal pieces, one of which is allowed to absorb all the recoil impact, while the other is removed from under the ball immediately after the first blow, by means of a string tied around it. The first body will suffer greater upsetting than the second, which is a proof that the impact of the ball acquired by dropping from the height which it reached by recoil is still sufficient to produce further permanent deformation. This could certainly not be the case if the recoil of the ball were produced by the elasticity of the test-piece alone.

f. Fractures.

253. Standard test-pieces of ductile materials assume barrel-shape during the upsetting-test, and as a rule one of the types shown in Fig. 188 (see *125* and *127*). In some cases the surface becomes "crinkled" (*106*). Clearly defined streaks, corresponding to the longitudinal seams of tension-tests (*124*) parallel to the axis of the test-piece, may be found on the mat surface of non-homogeneous rolled or drawn material when worked parallel to axis: they reveal harder and softer and sometimes more porous spots in material. In some alloys, e.g. impure lead, the surface becomes wrinkled to a greater or less degree, so that the body frequently assumes a very irregular appearance. Such appearance generally demonstrated that the metals did not alloy.

Fractures vary according to the properties of material. One or more cracks are produced in fibrous material, as in Fig. 188, *a* and *b*. In granular or brittle material such as cast iron, but frequently also in rolled material, cones are formed on the surfaces of impact which force a ring outwardly, frequently breaking it (Fig. 188, *c*). Many test-plugs of uniform tough material show diagonal cracks intersecting at 45° to the axis of the plug (Fig. 188, *f*). The indications of cracks are frequently apparent at a very early stage of the test, being preceded by very shallow diagonal grooves on the surface. Diagonal cracks are very marked in very tough gun-steel. A plug, *g*, Fig. 188, of this material was sawed through the centre before the cracks showed on the centre, then polished and etched; by reflected light the structure shown in *g* became apparent, but the markings were actually only visible with great difficulty, and indicated a lamination of the material, as that of an onion.

254. Examination of a tested plug reveals the formation of an exterior ring or collar on the ends struck, which is very plainly distinguishable from the inner circle, *c* and *d*, Fig. 188. This inner circle corresponds to the original end-surface, diameter $= d_i$, of the test-piece; the radially marked collar, exterior diameter $= d_a$, may contain particles which were originally contained in the shell.

Nearly all of these phenomena also occur during crushing-tests. The type shown in *c*, Fig. 188, having different diameters of faces, is certainly not so plainly produced during crushing-tests.

255. The type of phenomena of rupture also depends upon the shape of test-pieces.

This is true of tests of hard-drawn steel tubes cut square with the axis so that $l = d$. The progress of deformation was characteristically different for tubes of different dimensions, and was alike for upsetting- and crushing-tests, so that an almost definite variation of deformation was produced by definite variation of length of identical bodies. In spite of a

... which was in part accompanied by ...ations shown in Fig. 189 were pro- ... signs of failure; but few pieces in ... cracks. Fig. 189 shows three ... tube sections of different thickness. ... lating thereto are given in a compre- ... report (*L 155*, p. 40 et seq.). These ... that a special limitation of the law of ... the case of tests of nearly geometrically

... metrically similar bodies of ... material suffer geometri- ... milar deformations (Fig. 189. ... equal crushing e_s under equal ... equal specific impact."

... which the requirements of this law of simi- ... pproximately met gave closely coinciding dia- ... atio $l:(d - d_1)$ (length to thickness of tube) ... the shape of curve and of deformation* ... Fig. 189, *a–c*.

... Method of Test.

... before beginning tests the impact machine is to be ... in the first place for friction of guides as per ... Their coincidence of vertical axis of ball and ... be verified, and whether the two striking sur- ... ly plane. The three examinations may be ... simultaneously, by a single blow on a lead plug ... to take the impressions of both surfaces com- ... from these impressions the coincidence of axes of ... are determined, and measurements of thick- ... of four quadrants and at the centre, whether ... bounded by plane parallel surfaces. The sur-

... phenomena of producing folds have been utilized during ... tubes during flanging, by making the flange to follow the ... Fig. 189.

faces of impact of ball and base must be frequently ground true, and hence they must be so constructed that this work may be done accurately and expeditiously. The impact-surfaces and the ball-guides are to be wiped with a cloth containing graphite dust, before test, to invariably produce most nearly uniform conditions of friction.

To avoid recoil blows, a string is to be tied to the test-piece, which is to be withdrawn instantly after impact; the body is to be reversed after each impact, so that the surface struck by the ball will rest on the anvil-face during the next blow.

257. I deduced a number of rules for making upsetting-tests from my earlier investigation (*L 155*), which I here desire to replace by the following new propositions, agreeing with those now adopted by the Charlottenburg Testing Laboratory for dimension of metal test-pieces for crushing- and upsetting-tests.

Starting with the cube, I propose to use either cubes or cylinders in which

$$n = l\sqrt{a} = 1,$$

and for the case of retaining the standard plug (cylinder), i.e.,

$$d = l,$$

to make these plugs of the same volume as those of cubes stated in Table 22. This will simplify the tests and calculations in many cases.

Table 22.—Dimensions of Test-pieces for Upsetting-test.

Volumes in cu. in.	0.061	.2059	0.488	.9531	1.6470	3.9037	7.625
Side of cube l	0.3937	.5904	0.7874	.9843	1.1811	1.5748	1.9685
Proportional cylinder l	0.3937	.5904	0.7874	.9843	1.1811	1.5748	1.9685
Proportional cylinder d	.4449	.6653	.8898	1.1103	1.3347	1.7757	2.2704
Standard plug $l = d$	.4252	.6778	.8547	1.0670	1.2797	1.7087	2.1338

258. Upsetting-tests are to serve for the determination of the upsetting factor (*247*). Hence it is attempted to determine the sum of specific impact necessary to produce rupture or $e_i\% = 80\%$ by means of light blows. Heavier blows are then resorted to, these requiring smaller impact, until finally a single blow producing the desired result is found. A complete investigation therefore always requires several tests, which must be so selected as to determine the properties of the material amply, and to limit the labor as much as possible.

According to an earlier proposition the blows are to be so measured that the first of five test-plugs receives a specific impact of $1i$, the second of $2i$, the third of $4i$ for each blow. Suitable values of a were given as follows:

1. Steel of tenacity from 71,000 to 113,000 lbs. sq. in., $i = 118.4$ ft.-lbs. per cu. in. (= 1000 cm kg/ccm).

2. Wrought Iron, Cast Iron, Copper and Alloys of medium hardness, $i = 29.6$ ft.-lbs. per cu. in. (= 250 cm kg/ccm).

3. Soft metals, $i = 2.96$ ft.-lbs. per cu. in. (= 25 cm kg/ccm.

The remaining two plugs are then to be tested each by one blow in accordance with facts determined by the previous investigation, so as just to reach the upsetting factor.

259. Making a test according to this method, however, requires a large number of blows. Kirsch proposed to shorten it by the selection of different specific impacts for each blow, by using the above-stated values of i as a basis, denoting the number of the blow in the above series 1, 2 and 3 by Z_1, Z_2 and Z_3, and testing:

Plug 1, with increasing impact for each blow, so that the specific impact will be derived from $\frac{Z_1\, i \text{ ft.-lbs.}}{\text{cu. in.}}$;

Plug 2, starting with specific impact $Z_1 i$ of the last blow of series 1, with impact increasing with each blow according to formula $Z_1 i + (Z_2 - 1)i$;

Plug 3, starting with specific impact of the last blow of series 2, with impact increasing with each blow according to formula

$$(Z_1 i + [Z_2 - 1]i) + (Z_2 - 1)i$$

until rupture or $-e_i\% = 80\%$ is produced by a single blow.

This method certainly secures a smaller number of blows, but 5 plugs no longer suffice if the rule is strictly adhered to. Therefore I tried to combine both methods and proposed to the Zurich Conference for Unification of Methods of Testing Materials that the following method be studied:

Proposition *a*.		Proposition *b*,
Plug 1 by $Z_1 i$	or	$Z_1 i$.
Plug 2 by $Z_2 2i$	or	$0.5 \Sigma Z_1 i + (Z_2 - 1)\, i$ ($0.5 \Sigma Z_1 i$ from 1st series).
Plug 3 by $Z_3 4i$	or	1 blow producing rupture or $-e_i\% = 80\%$ (by estimation from 2d series).
Plugs 4 and 5		1 blow producing rupture or $-e_i\% = 80\%$ (estimated from previous series.)

In order to test the four propositions I had a series of tests made with plugs of different materials but of identical dimensions according to each of the four methods proposed, and thus obtained the results in Table 23, plotted in Fig. 190.

According to these results I hereafter recommend the methods under *C* and *D* for upsetting-tests, and simplify my old propositions for the values of i to:

1. For soft metals (lead, etc.)........$i = 2.96$ ft.-lbs. per sq. in.
2. For cast iron....... ....$i = 29.6$ " " "
3. For copper, bronze and soft alloys $i = 59.2$ " " "
4. For iron and stronger metals......$i = 118.4$ " " "

If larger values of i become necessary in special cases, it is advisable to use a multiple of $i = 59.2$ ft.-lbs. per sq. in.*

Table 28.—Comparison of 4 Propositions for Making Upsetting-tests.

Z indicates the number of the blow; Σi = the sum of specific impacts of all blows in ft.-lbs. per cu. in.

<table>
<tr><th rowspan="3">No. of Plug.</th><th colspan="4">Values of i according to proposition of NN will become:</th></tr>
<tr><th>Martens (original).</th><th>Kirsch.</th><th colspan="2">Martens-Kirsch, combined.</th></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr><td>1</td><td>$1i$</td><td>$Z_1 i$</td><td>$Z_1 i$</td><td>$Z_1 i$</td></tr>
<tr><td>2</td><td>$2i$</td><td>$Z_1 i + (Z_2 - 1)i$</td><td>$Z_2 2i$</td><td>$\left\{\begin{array}{l}0.5\,\Sigma Z_1 i\\ + (Z_2 - 1)i\end{array}\right.$</td></tr>
<tr><td>3</td><td>$4i$</td><td>$\left\{\begin{array}{l}Z_1 i + (Z_2 - 1)i\\ + (Z_3 - 1)i\end{array}\right.$</td><td>$Z_3 4i$</td><td>1 blow</td></tr>
<tr><td>4</td><td>1 blow</td><td>etc.</td><td>1 blow</td><td>1 blow</td></tr>
<tr><td>5</td><td>1 blow</td><td></td><td>1 blow</td><td>1 blow</td></tr>
<tr><td></td><td colspan="4">Tests to be continued to rupture (cracks or destruction), or until $-e_i\% = 80\%$.</td></tr>
<tr><td></td><td colspan="4">Results of Comparative Tests demonstrated that:</td></tr>
<tr><td>a) in general:</td><td>The total number of blows for the complete test is very great.</td><td>Following instructions conscientiously will require numerous test-plugs.</td><td colspan="2">Both methods shorten the test materially, which can be made with 5 test-plugs.</td></tr>
<tr><td>b) Test of low steel (Flusseisen): $S_M = 79,400$ lb. pr. sq. in. $l = d = 0.507$ in. $i = 118.4\,\frac{\text{ft.-lbs.}}{\text{cu.-in.}}$: required:</td><td>Required blows for complete test:
55 blows</td><td>Was not determined</td><td colspan="2">Blows required for the complete test:
C: 15 blows   D: 11 blows</td></tr>
</table>

Very few upsetting-tests have been made with materials other than metals, but it is highly probable that they would

* Objection was made at the Zurich Conference (1895) because no definite values of h and W were given. This would have complicated matters. These directions also appear unnecessary, because upsetting-tests made on such small plugs as here presupposed would hardly be made on a large impact machine, because moreover the height of drop is generally limited very closely by the height of buildings containing them.

produce valuable information, e.g., of stone (*L 156*, p. 50), bond materials, mortars, etc. Hence definite propositions for making such tests cannot as yet be made.

4. Impact Tension-test.

260. Impact tension-tests, according to my information, were first made by Gen. Uchatius of Austria for testing materials. They are very rarely made, and only regularly in one case, that of testing bolts for fastening armor-plate to ships' hulls. In fact it cannot be expected that scientists would recommend them very warmly, because it will be very difficult to construct an impact machine for tension-tests in such manner as to make it easily discernible which part of the impact is absorbed by the test-piece. The blow cannot be made to act directly on the test-piece, as intermediate pieces are required, which on one hand connect the test-piece rigidly with the anvil, and on the other receive the force of the blow to transmit it to the test-piece. Hence I again refer to (*230*) and (*232*), and to the work of the Charlottenburg Testing Laboratory relating to impact tests of wire rope and rope connections, published in the "Mitth. Berlin" (*L 153*).

261. The Charlottenburg Laboratory has repeatedly had occasion to make impact tension-tests of standard round bars (0.8 in diam., $l = 11.3\sqrt{a}$) of low steel (Flusseisen) and bronzes. Individual series of tests have been plotted in Figs. 191 and 192, in a manner similar to that used in the diagrams of impact tension-tests plotted according to principles developed in (*252*).

Three series of tests, a, b and c, are plotted in Fig. 191, which refer to aluminum bronze of varying compositions, while Fig. 192 shows curves for low steel (Flusseisen), lines d, and the lines a, b and c for bronzes on a different scale. The plotting was done so that the heavy lines show total specific

impact Σi in $\frac{\text{cm kg}}{\text{ccm}}$*, which the material absorbed, as ordinates, and the elongation $e_i\%$ as abscissae (hence in direction of axes X and Y, Fig. 180). The fine broken lines, with same letters show the $e_1\%$ for each blow plotted on a tenfold scale. They show that the impact tension-tests of bronzes were made in three and two steps, with different specific impact for the blow; it is easily seen that the effect of successive blows decreases within each group; the $\Delta e_1\%$ become less, precisely as in upsetting-tests.

Characteristic differences in the materials may be represented by the differences in $-e_{fi}$ (as was done by e_f in tension-tests (*34*)) produced by the unit impact; it must, however, always be remembered that these values depend (as appears from the curves $\Delta e_1\%$) upon the conditions under which the test was made. These values are shown in Figs. 191 and 192 by fine full lines. The readings obtained from the curves for these values must be multiplied by 10^{-3}, i.e., the value 0.1 represents $-e_{fi} = \frac{e_1\%}{-e_f} = 0.0001$.

262. It has been pointed out in (*261*) that the effect of secondary conditions under which the impact tension-tests were made becomes more pronounced. If, therefore, comparable results are desired, it is always most advisable to use identical apparatus, sections and dimensions, under identical conditions, for it would be very complicated and expensive if it were necessary to determine the laws of effect of each condition in a manner similar to that done for the upsetting-test. We may,

* These diagrams are not changed to $\frac{\text{ft.-lbs.}}{\text{cu. in.}}$, because the curve would in any case be identical, and their general character alone is here considered. The volume is calculated as that of the cylindrical part of bar only; in fact the conical necks also absorb a part of the impact and show deformation. The letter k indicates that the material becomes "crinkled"; e indicates the beginning of contraction.

however, draw the conclusion from the above that it does not, for example, suffice to prescribe conditions relating to shape of sample and method of test, but rather for each part of the impact machine, if tests of armor-bolts alone are concerned, when it is desired to deal with manufacturers on equal terms; manufacturers would do well to make certain that check tests at other places are not made so as to be to their disadvantage.

263. The impact tension-tests made at the Charlottenburg Testing Laboratory have convinced me that changes of shape are exactly alike to those occurring in tension-tests under steady load. Indeed, the capability for deformation of certain materials, e.g., low steel (Flusseisen), even under rupture by a single blow, is apparently not affected; when rupture was produced by several blows elongation was frequently found to be greater than in tension-test. This observation cannot, however, be applied to all material.

264. Phenomena of fracture are identical in impact tension-test and in tension-test under steady load.

265. In case of impact tension-tests the total impact of a number of blows of definite specific impact, producing rupture, may be used as the quality factor. The factor of rupture for impact tension-tests, i.e., that specific impact which just ruptures the test-piece, is still more appropriate.

5. Impact Transverse-test.

a. Method of Tests.

In General.

266. The impact transverse test (commonly called "drop-test") is one of the earliest methods of testing. It is generally made by placing a bar across two supports, dropping the ball so as to strike it at the centre. The number z of blows required to produce rupture, or a definite deflection, or the necessary impact $zA = zhW$ in ft.-lbs. are noted.

The method of measuring deformations depends upon the kind and shape of test-piece. The deflection δ of beams is measured at their centre. Several methods are used for this purpose, which give different results.

267. In the Charlottenburg Testing Laboratory, in conformity with the practice of the custom of many public laboratories, Bauschinger's method is used. This method (180) provides for measurements at three points $a\,a_1\,a$, Fig. 193, of which a and a, separated by distance between supports, and a_1, half-way between them, are marked on that line of the side corresponding to the neutral axis of the bar. The length l_1 of the chord $\overline{aa}$ and the distance δ_1 of the point a_1 from the chord $\overline{aa}$ are measured by a three-legged compass.

268. It would better agree with the theory of resistance of materials if the second method of measurement were used, and taking the same measurements on points $c\,c$ above the bearing-points, so that the length of chord $\overline{cc}$ would remain $= l$, and the distance δ of point a_1 from the chord $\overline{cc}$ be measured.

But as the bearings must never have sharp edges, because they would be worn off rapidly or might injure the test-piece, the bearing-length is constantly decreased during deflection, and in proportion to the rounding of the bearings, as shown in Fig. 194. Hence this second method would not give results agreeing closely with theoretical considerations. Moreover measurement of deflection loses practical value for the constructor as permanent deformation becomes more pronounced.

For purposes of judging of material, which can never be anything but comparative, the error committed is of less importance; it is only essential that the same method has been invariably used.

Hence the following two simpler methods are used in routine work.

269. In the first method a straight-edge of length l is placed upon the upper surface of test-piece, its ends touching

points dd, Fig. 193, and distance δ_2 is measured. Occasionally two knots in a string denoting the distance l are placed above dd, and the distance δ_2 from the surface of bar is then measured. Railway managements prescribe the use of a straight-edge carrying a slide at its centre by which δ_2 is indicated.

270. In the second method the points $\overline{b\,b}$ mark the length l on the straight bar, and deflection δ_2 is then measured from a string passing through them.

When not otherwise stated, measurements of deflection given in this book have been made by the method in (*267*).

Testing Railway Material.

271. Since railways have again returned to the use of the drop-tests (impact transverse tests) they have assumed greater importance, and hence the rules adopted by the German railway managements for making drop-tests for testing road material and rolling stock shall be here reproduced. The essential instructions are about as follows:

1. The source, the material, the general dimensions and cross-section of the body are to be accurately stated.

2. For rails $l = 1$ m (3.28 ft.), total length $L = 1.3$ m (4.26 ft.) (the test-piece is not to have any splice-holes); for axles l is to be $= 1.5$ m. (4.42 ft.).

3. Deflection of axles and rails is to be measured from the upper surface, and always in relation to original distance between bearings [as in (*268*)]. In order that the test-piece remain uninjured the riders are provided (*226*, No. 9) with a planed groove 1.3 cm (0.50 in.) in width,* Fig. 195. A beam-compass with a middle leg having a vertical slide divided into millimeters is recommended for measurements. Measurements shall be made after each blow.

4. In impact-tests of rails blows of 1500, 1000 or 750 mkg (10,800, 7200 and 6400 ft.-lbs.) are used for rails exceeding 48

* Specifications for rails of 1896 no longer mention this groove.

lbs. per yd.; from 48 to 40 lbs.; and of 32 lbs.; for axles impact of about 21,650 ft.-lbs., blows are always to be given on the same side of test-piece. (Formerly it was customary to reverse the piece after each blow.)

Locomotive-axles are tested under 39,750 (23 ft. × 1760 lbs.) (5600 mkg = 7 m × 800 kg), tender-axles under 30,280 (23 ft. × 1320 lbs.) (4200 mkg = 7 m × 600 kg). *

5. Tires (placed in position under drop vertically) impact of 21,630 ft.-lbs. (3000 mkg) is to be used [and riders (*226*)]; after each blow the vertical depression and lateral spreading are to be measured on internal diameters by a sliding caliper provided with mm divisions.

6. About one third of the pieces are to be tested to rupture; when necessary, rupture of rails, axles, and tires is to be induced by nicking.

7. Uncommon phenomena of deformations of test-piece and of fracture are to be minutely examined and described, as well as the thermal condition of test-piece during test.

8. Finally, tension-tests are prescribed, additional to impact-tests, and the necessary test-pieces are to be obtained from those parts of the material tested by impact which have suffered least. Test-pieces cut from tires from the parts which have been least bent may be straightened under slightest possible heating necessary.

9. In order to obtain a knowledge of stress and deformation of material, spacing-lines are to be provided before tests at points of maximum deformation, by which extensibility and crushing are to be determined. Hence in rails centimeter divisions are to be marked off on the heads, at their centre, Fig. 196. After test the extension and crushing is to be determined from measurements of a, b and c, etc. The half-inch

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* In this case, differing from the principle adopted elsewhere, the factors H and W are adopted instead of the impact, and in such manner that balls must be interchanged when tests of locomotive and tender axles are to succeed each other.

groove of the rider (Fig. 195) is also intended to protect this spacing.*

b. Phenomena of Flow and of Rupture.

272. Superficial phenomena of flow become apparent in the bending or impact-bending test after passing the yield-point, similar to those noted in the tension-test .As the material is stressed above the yield-point in the transverse test only in a local manner near the point of maximum stress, it is often possible to obtain an accurate indication of distribution of stress by careful observation; causes of rupture of parts of structures may frequently be determined by the appearance of stress-lines at the fracture. Although studies of phenomena of flow have been by no means concluded, it appears advisable to call attention to these occurrences to stimulate further development (*L 120, 122*).

273. When a polished bar of soft low steel (weiches Flusseisen) suffers permanent deflection it becomes covered with flaming branched figures, Fig. 197, of semicircular shape or patches. These figures approach each other at the neutral plane, where a strip generally several millimeters in width (more than $\frac{1}{8}$ in.) remains unaffected, being an indication of the fact that the stress near the neutral plane does not reach the yield-point during great deflection (Plate 2, Fig. 41).

724. In case of rails and other bars still covered with mill-scale, as well as in tension-tests, the scale is shed at the points where yielding occurs. Flow of metal may sometimes be very clearly traced on such pieces, Fig. 198. These two circular patches appear, but curved radiating lines also occur in the cusps, which are crossed by other lines normal to them (Plate 2, Fig. 42). These lines give an indication of the patches and prove, as has already been shown in tension-tests

* Rail Specifications of the Prussian State Railways, 1896, do not contain these directions.

. . . e continuous, but is intermittent in
. . . n which certain groups of parti-
. . . eries suffer relative displacement.
. . . arly arranged lines which intersect
. . . tress-patches were produced in iden-
. . . s in them are so closely arranged that
. . . shed when the last rays have devel-
. . . e cusps (*L 120*).

. . . se occurrences which follow laws with
. . . might be advisable, particular attention
. . . ds of low steels (Flusseisen) which are
. . . den transition at the yield-point, shown by
. . . t from those which do not show this sud-
. . . materials should show characteristic differ-
. . . ay desire at this place to again recall the
. . . at flow is related to physical and chemical
. . . *8* and *120*). It is remarkable how easily
. . . s corrode, so that the stress-lines are occasion
. . . after corrosion (*159*).

. . . e-phenomena and types of im
. . . s agree precisely with those obtained during
. . . steady load. Prismatic bars of low steel
. . . fractures depending upon structural differ-
. . . own in Fig. 199 * are obtained most commonly:

a) Straight fracture ;
b) Irregular fracture ;
c) Triple fracture.

. . . two types of fracture may be considered as modi
. . . third ; compare dotted lines in Figs. *a* to *c* and
. . . and 28. The law underlying these types will
. . . more apparent upon assembling fracture-types
. . . impact bending-tests of rails (*L 122*).

* . . . illustrations by Bach (*L 138*, 1888, p. 1092, Figs. 1-3)

Fig. 200 A shows all usual types of fractures; the principal shapes are especially shown in Figs. B to E. It will be seen that fracture follows the edges of stress-patches very closely. Ideal fracture, as shown by A, should consist of four pieces. Sometimes these are actually obtained, though as a rule one of the small lower pieces remains attached to one part of the rail a or b, thus producing the fractures shown by B to E. If, however, the pieces b and c are formed, Figs. B, E and D, it is usually apparent that there was an effort to rupture on the dotted lines. If rupture occurs clean, across the section following the dotted line Fig. A, so that $c/2$ and $d/2$ adhere to a and b, it is called a smooth (plane) fracture, also called "fracture square with axis" at the Charlottenburg Testing Laboratory. If the pieces c or d remain adhering to a and b, it is called irregular fracture or oblique with axis. A special form thereof is shown by Fig. D, in which $c/2$ is wanting and $d/2$ in evidence. Occasionally the pieces e break off the foot or flanges, Fig. F, which frequently show checks along the dotted lines (Pl. 2, Figs. 31–41 and 43).

276. Fracture-lines, as found in tension-tests (*121*), are found in all fractures produced by bending- and impact bending-tests. They are most clearly marked in fine-grained material. Pl. 2, Figs. 27, 28 and 31 show such fractures produced by bending-test. It is seen that, in this case also, the lines emanate from one point of the tension-edge of the fracture as in Fig. 80, and radiate across the entire surface, ultimately terminating in lines almost normal to the fractured edge. The fractures form more or less marked, bent, concentric waves; the fracture-lines are sharper and more clearly marked in the troughs: they appear to be split on the ridges. The details of these phenomena become more distinct in fractures produced by repetitive tests. They shall therefore be discussed more fully in Section *i*, treating of repetitive tests.

c. Effect of Velocity.

277. As was emphasized in (*242*), Kick (*L 100*) g tests from which he concludes that velocity of impact ex but an immaterial effect on magnitude of deformation.

Rotter made several series of impact transverse t with small specimens, which may be used to study whe Kick's conclusion also holds good in these. Rotte tests are plotted in Fig. 201. These tests were made on i tical test-pieces, supported on a span of 8 in. (20 cm), three balls, 22, 44 and 88 lbs. (10, 20 and 40 kg) weight, u $h = 9.8$, 19.6 and $39\frac{1}{2}$ in. (0.25, 0.5 and 1.00 m), and alway such number of blows that total impact was equal to 2 ft.-lbs. (40 mkg). Deflections δ produced by these impacts plotted in A, Fig. 201. From these the curves of aver marked h were derived. These lines must originate in c ball of weight 0 produces $\delta = 0$. Similarly curves B drawn, arranging them according to h and δ. These l show the deflections obtained with the different balls by total impact of $A = 288.4$ ft.-lbs. (40 mkg); these lines m also originate in 0. Fig. C (dotted lines) shows the project of the volume deduced from the two former series, and wl represents the law deduced from Rotter's tests goverr the dependence of deflection of identical bodies produced total impact of 288.4 ft.-lbs. upon the values of the indivic factors H and W.

278. Fig. 201 shows that effect of identical impac by no means the same under varying conditions obtainable different execution of test. It varies with the weight of ball height of drop. Moreover, the effect is not the same ur equal impact for each blow. The fine dotted hyperbolic l represent curves of identical product $H \times W$, i.e., ident impact for each blow. They at the same time indicate number of blows necessary to produce total impact 288.4 ft.-lbs. (40 mkg), and they are marked by these numb

They intersect the full lines, marked at upper or lower ends, which represent curves of equal deflection. This would not be the case if deformation depended simply upon the value of $A = H \times W$.

279. From these curves the following laws may be deduced:

a. Heavy blows produce greater deflection than a greater number of light blows of equal impact (see *245*).

b. Under equal impact $H \times W$ of blow heavier weights of ball produce greater deflection.

Rotter also made a series of tests of harder low steel haerterem Flusseisen), producing rupture with x blows of identical total impact. To produce rupture, less total impact was necessary in case of heavy blows than under light blows. Here also, with identical impact per blow, the total impact producing rupture was less when using heavy balls than when using those of lighter weight. Hence it is again found that results obtained from upsetting tests are corroborated.

d. Effect of Shape of Test-piece and the Law of Similarity.

280. Thus far sufficient tests have not been made to determine the influence of shape of test-piece, and to what degree the law of similarity applies in impact bending-tests. That shapes of test-pieces must be selected according to definite principles based on the law of similarity, which here applies in the same form, is, however, plain. If variations from this law are found, this will always be caused by the reason that the gross-impact of ball can alone be measured, and that a part varying according to circumstances is invariably lost. This part might vary in each blow of equal impact, according to the part played by the weight of ball W in the equation $A = H \times W$. The law of similarity deals primarily with the net impact, i.e., that amount of impact which is actually required to produce deformation.

281. One circumstance which must affect deflection is produced by the projection of the ends beyond the points of support, Fig. 202, which because of their inertia remain at *b* below the position due to deflection *a*, produced by impact, and then spring beyond this position to point *c*. The magnitude of this action depends upon the length of the projecting ends. Recognition of this circumstance caused the railway managements to prescribe the length of 4.26 ft. (1.3 m) for impact-tests of rails (*271*, 2). For axles such rule was not necessary, as they always have definite lengths.

g. Effect of Speed in Tests of Resistance.

282. The question of effect of rapidity of production of deformation on results of tests has been repeatedly touched upon, that is, on the value of stress at the proportional limit, yield-point, and maximum load, or upon the value of elongation and contraction. This question is of course of the greatest practical importance in testing materials.

283. Recalling what has been said (*53*) about the behavior of magnesium under tension-test, the fact that there is very considerable residuary extension after each load applied intermittently, which occurs with different rapidity, decreasing at first, but increasing with increasing loads, must permit us to conclude that speed of testing must affect results of tests.

284. There must be intermolecular motion during deformation, and individual elements must assume new positions to make permanent deformation possible. After having become familiar with the adjective "flow, flow-phenomena," it will not appear strange to regard the solid body, to a certain extent, as a very viscous liquid. This can be illustrated at any moment by testing materials which are transitionary between the solids and liquids. Pitch behaves as a solid and is brittle under a load quickly applied; it breaks like glass

with conchoidal fracture. If lumps of pitch be placed in a vessel and left untouched for some time, they will change their shape and ultimately unite into one mass, to form a surface just like a liquid. If the vessel be then inclined, the pitch will run out in a couple of weeks, as though poured out, although the flowing thread would show the brittleness of a solid if it were attempted to change its shape suddenly.

285. Toughness or internal friction of the liquid must be overcome if its particles are to be set in motion. If the particles are to move faster, acceleration of motion will be produced by increased pressure. The occurrences in a solid may be conceived to be quite similar. A certain force is requisite to overcome internal adhesion, ultimately producing rupture. If it is to occur in a shorter period of time, it will be necessary to accelerate the flow of particles by adding additional force.

This consideration is convincing that a greater load must be applied to produce identical deformation in a shorter period of time, and as $\frac{L}{a} = S$, greater stress must be produced in the test-piece.

286. It is, however, questionable whether this increase of stress is of such magnitude that it is noticeable for the practical purposes of testing. Many tests have been made to answer this question, of which I shall only refer to the more extended series of Bauschinger (*L 160*), of Fischer (*L 161*), and to a few made by myself.

287. Diagrams obtained from tension-tests of sheet zinc are like those in Fig. 203. If parallel strips be tested in tension, and at three different speeds v, v_1 and v_2, three different curves, which are very similar, will be obtained (*L 115*). Stress will increase with speed. In case of zinc the tensile strength S_M may be doubled by increasing the speed. Fischer (*L 161*) proved similar results for tin. Hence reports of tests of these

materials **are as good as valueless for judging their quality** unless obtained under **identical speed**, and unless they are at the same time stated.

288. If iron and steel be tested similarly, ordinary machines will not permit the determination of any effect of speed unless a very great number of tests be made of identical material, because the differences of strength of pieces, cut side by side from the same sheet, are generally so great that the effect of speed lies within these errors. The differences in resistance obtained by slow and rapid tests can only be determined by machines of proper construction when tests are made on one and the same piece to determine whether more rapid rate of flow requires a greater load on the weighing-machine.* Not every scale is suitable for this purpose.

In order to make the test in the manner indicated, by sudden change of speed during the test of a bar, without material error, the masses of the weighing mechanism should be small, and it should not be so constructed that the weighing mechanism may assume the function of the straining mechanism; i.e., to load the test-piece in a manner not contemplated.

289. If the weighing mechanism has too great a mass, the inertia will affect the functions of weighing mechanism during a change of straining-speed, and the results will have to be carefully tested and corrected in this respect. Very small masses result from the use of springs as load-indicators (*65, e*).

290. If, however, a spring such as a spiral spring, which has great motion when relieved, be employed for this purpose, its indications could not follow sudden changes of speed of straining mechanism. The test-piece would continue to be strained by the spring under sudden arrest of the straining

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* See (*110, c*).

mechanism, until the spring had been sufficiently relieved, that its force could no longer produce strain of the bar; hence the intended straining-speed would not be equal to 0.

It will be seen that unfavorable design of spring may even produce rupture of bar without having reached the intended straining-speed 0; in the case where the travel of the spring up to release, to the tensile resistance S_R (*39*), is greater than the extension of bar at instant of rupture. Under sudden increase of rate of straining of the mechanism, the straining-speed in the bar will not immediately reach the intended speed, and in fact it must travel a definite amount equal to the stress corresponding to the intended straining-speed.

If a weighing-device having a minimum motion for complete release be employed, the conditions just described will be most favorable. A steel bar under tension answers these requirements, as employed by me in a small tension machine* in the Charlottenburg Testing Laboratory (*115*), and also the device used in the 50-ton machine (*L 162*, Pl. 5) which I constructed for the same Laboratory.

291. If a strip of zinc be tested in a machine of this type, and alternately strained fast and slow by driving the machine fast or slow, the diagram recorded will assume the approximate shape shown in Fig. 204. At the moment of change of straining-speed v_1 to the lesser speed the pencil will drop instantly, and then records that part of the curve marked v, and again rising with equal promptness to line v_2 under change of speed from v to v_2, etc., etc. The differences in ordinates thus directly give the effect of straining-speed on the results of tests. In case of tin, zinc, and similar metals it is very considerable.

292. If iron or steel be tested in a similar manner, the breaks in the diagram will be hardly noticeable. The effect of speed will hardly amount to 1 to 1.5% according to

*This bar elongates 0.024 in. (0.62 mm) under maximum capacity of the machine $L = 2200$ lbs. (1000 kg).

the tests of iron thus far made by me. Bauschinger (*L 160*) has confirmed the effect of speed on tests of zinc and a few other metals, and demonstrated that it may be neglected in case of practical tests of materials of construction.* †

293. This is a matter of very considerable importance in testing materials, as no great importance need therefore be attached to maintaining a definite straining-speed in routine testing. In fact, tension-tests are nowadays made in a few minutes. It is, however, desirable that public testing laboratories adhere to the rule adopted by several of them to use definite straining-speeds. A strain of 1% per minute has thus far been customary; but it may be necessary to adopt 2% per minute, because otherwise tests will become too tedious and expensive.

294. What has been stated relating to tension-test is no doubt equally true of all other tests of resistance. In these the influence undoubtedly exists (*218*), but it has been thus far studied but slightly.

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* I should like to call particular attention to the fact that conclusions refer to the behavior of the material alone, and not to the behavior of the testing-machine. This is quite a different matter, and my experience has been that the speed is a material factor in the results of tests made on all multiple-lever machines. The precise amount of this effect has not been determined. Remembering that straining-speeds of more than 25% per minute are now in common use in England and the United States, the problem is quite a different one from that discussed in the above by the author, and by the investigators referred to, who, all of them, use machines which cannot be operated at more than moderate speeds. The 2200-lb. machine referred to cannot be operated at any great speed.—G. C. Hg.

† Having referred this matter of effect of speed to Prof. Martens, he requests me to emphasize that such speeds as are in common use in England and the United States (15–25% elongation in one minute) must undoubtedly produce a noticeable effect; and also that his and Bauschinger's tests were made with speeds very materially lower than the above. Formerly 1% per minute was the rule at the Charlottenburg Testing Laboratory; it is now about 2% per minute. Under these conditions alone the above statement is admissible.—G. C. Hg.

Although numerous investigations of the influence of straining-speed on tension-tests have been made, the data are not only discontinuous, but also not free from objections, for reasons stated in (*288*) to (*290*), and it is very desirable that the tests be extended. Individual investigations cannot, however, be here discussed; this must be deferred to the special discussion of properties of materials.

h. Resistance-tests under High and Low Temperatures.

295. Materials of construction are very often used at temperatures which vary greatly from the average, to which alone all tests and statements heretofore discussed have been assumed to refer. In ice-machines, in gas-liquefying machines certain parts are exposed to very low temperatures; bridges, rails, tires, and all other possible material is subject to variations of temperatures from $-13°$ to $+95°$ F. ($-25°$ to $+35°$ C. in Germany). In the United States these are $-40°$ to $+130°$ F. In boilers and kettles of all descriptions temperatures may easily range from $-13°$ to $+400°$ F. ($-25°$ to $+200°$ C.); in steam-superheaters 750° F. (400° C.) and more may be reached; in case of conflagrations material must resist even very much higher temperatures. In heating- and melting-furnaces the furnace materials must in fact, while at a white heat, resist important stress and shock. A knowledge of the strength of materials under these conditions is therefore of great value to the constructor. But it is also very important to the technologist, for the resistance and ductility of raw materials when hot, to determine the manipulation during rolling, forging, etc., etc.

At this place the general provisions adopted for making tests under extraordinary thermal conditions can only be hastily discussed. The changes of properties of the most important materials of construction due to thermal changes shall be discussed later on, when discussing properties of materials.

296. Freezing-mixtures, such as salt, snow, or crushed ice, are usually employed to produce low temperatures, temperatures of from $-4°$ to $-6°$ F. being thus obtainable. At present carbonic acid snow is used advantageously, being produced by allowing liquefied CO_2 to pass through velvet bags. Thus temperatures as low as $-112°$ F. ($-80°$ C.) may be easily obtained, and also maintained constantly by wrapping the bag about the test-piece and surrounding the latter uniformly with snow by use of the hands. Liquid air makes temperatures of $-312°$ F. available.

297. As a rule, however, tests are made by use of baths, which maintain the test-piece at a uniform temperature for a long time. If the test is to be made very rapidly, as, for example, in case of impact-tests, it is customary to raise or lower the temperature somewhat beyond the desired point and then, if possible, redetermine it immediately after test, in order to obtain some knowledge of thermal condition at instant of test. The first case is usually done in case of impact-tests, and the technological tests (Division *B*) still to be discussed; the second case is generally adopted in tension-tests, especially when elastic properties are to be determined at the same time.

298. Tests at temperatures up to 572° F. (300° C.) are made by use of liquids of high boiling-points (*L 163*). At higher temperatures alloys of low melting-points may be sometimes used under proper circumstances, or even salts. Mixtures of nitrate of soda or potash (*L 164*) is suitable for temperatures up to 930° F. (500° C.): this, however, attacks metals in course of time. Higher temperatures would, as a rule, be produced by gas-furnaces which envelop the test-piece. Electric ovens have also been used.

299. The devices used must be in most cases fitted to special conditions existing in testing-machines available. If I here discuss a few of such devices they can only serve as illustrations, which I shall simplify by naming their sources.

a. For testing iron under high temperatures (*L 165*) the

apparatus shown in Fig. 205, attached to a conical part of the test-piece, was used at the Charlottenburg Testing Laboratory. It consists of an iron stove having two walls, the inner chamber being about 4 in. (10 cm) in diameter, and is filled with paraffine for tests up to 392° F. (200° C.), or with a metal bath for tests up to 1112° F. (600° C.). This vessel was enclosed by an iron jacket having slots through which the jets of two Mundscheid blast-lamps were forced. These small convenient blast-lamps mix the gas and air by means of perforated disks, and this mixture was blown into the ovens by suitable orifices. The compressor is driven by a small turbine mounted directly on the axis. Slides controlled the inflow of air, and a stop-cock that of the gas; the emission of gases of combustion is also controlled by slides. Each of the two slit-burners emitted a sheet-flame of about 4.4 in. width (11 cm).

b. As this oven was intended for a special investigation and only unusually large test-pieces could be used in it, and it became desirable later on to use it in regular tests of heated metal, using smaller bars, it was finally modified as shown in Fig. 18, Pl. 5. In this case large Bunsen burners were used, three of which are mounted on the gas-chamber, and are supplied with regulation for air and for gas. The flames enter the heating-chamber, surround the bath (paraffine or salt mixture), and then escape through the jacket of the oven into the chimney, provided with a damper, which can be revolved into any convenient position. In this case this oven also depends from the test-piece by means of two prolongations on the shoulders, the lower one of which is rigidly connected with the oven. The test-bars have a special shape, and are made accurately to gauge in every detail; threads are cut on the heads, which fit into the spherical wedges of the jaws. Special tools are used to insert the test-pieces into the oven and to remove the broken parts.

300. To make measurements of precision by mirror apparatus possible, they are provided

with long spindles (*87*, *88*), so that the mirrors are quite distant from the oven, and the vibrations of the hot air rising at the oven do not affect the readings. The clamping-springs 2, Fig. 206 (see also Fig. 205,*A*), have a little different shape and arrangement. In order to secure a safe attachment the test-piece is provided with circumferential grooves. into which the knife-edges of the springs fit, Fig. 205, *A*. The principle of marking the gauge-length l_g on the finished length (*130*) had to be discarded, and the errors thus introduced were eliminated by calculation. The arrangement of mirror apparatus and their support on the frame of the machine is shown in Fig. 206. Identical numbers in the figures refer to identical parts. A description of the details of the mirrors will be found at the end of the book, in the chapter relating to measuring-instruments.

301. Many tests have been made to determine the resistance of columns of different materials and of various shapes under the effect of fire. I shall here refer to the tests of Bauschinger (*L 166*), Moeller (*L 167*), and of the Building Commissioners of Hamburg, Germany (*L 168*), which have materially aided in determining the safety of columns exposed to fire. Special arrangements were made for all of these tests, detailed description of which should be studied in the sources, because they are not of general interest. Bauschinger and Moeller tested columns horizontally, wood fires enveloping them. Bauschinger used the Werder machine, while Moeller used an hydraulic press ordinarily used for pipe-tests. In the Hamburg tests the columns were tested vertically; they were enveloped at the centre by a gas-oven, by which they were heated to the desired temperatures. In all of these tests the protective properties of poor heat-conducting materials were also studied; wood, stone, wrought- and cast-iron columns were tested.

302. The determinations of unusual thermal conditions have always given special trouble in testing the strength of

materials. But as improved apparatus for thermic determinations have lately been developed, this difficulty has been considerably modified. Formerly awkward water-calorimeters, fusible material, and air-pyrometers had to be used; the expansion of bodies by heat, fire-colors, and many other things were utilized. For rough practical tests, when comparisons only were attempted, many of these methods are convenient. Therefore attention is called to the following brief reference of the subject.

303. Melting- and boiling-points of certain materials may be used as a guide to thermal conditions of bodies. Evaporation of solidified carbonic acid gas takes place at − 176° F. (− 80° C.) [liquefied air and gases produce temperatures as low as − 392° F. (− 200° C.), melting mercury about − 102° F. (− 39° C.)].

304. Alcohol-thermometers measure cold; modern mercurial thermometers measure from − 86° F. (30° C.) to + 868° F. (500° C.), after specially suitable glass was discovered, which at the same time materially reduces instrumental errors. Mercurial thermometers for high temperatures are filled with highly compressed carbonic acid gas. Special "thread-thermometers" may be used as auxiliary to these, which admit of a simple and rapid correction of error which is produced by the length of the projecting thread. Thermometric observations up to 868° F. (500° C.) are then only subject to very small inaccuracies (*L 164*, p. 79). It is extremely convenient and highly to be recommended to have all instruments intended for accurate work compared by the Imperial Physico-Technical Institute at Charlottenburg, Marchstr., with the air-thermometer, repeatedly if possible. The sources of errors, their causes, their limiting values, and corrective calculations cannot be here considered, and reference is made to handbooks on physical laboratory work which are noted in the bibliography (*L 103*, *104*).

305. The German Gold and Silver Smelting Works at Frankfurt o. M. furnishes series of paper-thin rolled sheets of alloys of precious metals, stamped with definite melting-points. The melting-points are said to lie between 535° F. (315° C.) and 2668° F. (1500° C.); it will, however, be well to consider these values merely as approximate. Table 24 gives the statements of these works for individual alloys. Small strips are cut from the sheets and placed in fire-proof crucibles (tile-chips) filled with sand or magnesium, or embedded in clay lumps. In this condition they are exposed to the heat to be determined. It is noted which of the alloys melt into a globule. Mere bending of the strips takes place in some alloys below the melting-point; this should not be confused with melting into a globule.

Table 24.—**Metallic Alloys for Approximate Determination of Temperatures for Ceramic Purposes.**

Prinseps' metal-pyrometer, manufactured by the German Gold and Silver Smelting Works, Frankfurt a. M.

Melting-points in F.° and C.° according to Ehrhard and Schertel.								
	F.°	C.°		F.°	C.°		F.°	C.°
Cd.............	599	315	900 Au + 100 Pt	2066	1130	400 Au + 600 Pt	2660	1460
Zn	774	412	850 " + 150 "	2119	1160	350 " + 650 "	2723	1495
Al	1148	620	800 " + 200 "	2174	1190	300 " + 700 "	2795	1535
800 Ag + 200 Cu	1562	850	750 " + 250 "	2228	1220	250 " + 750 "	2858	1570
950 Ag + 50 Cu.	1652	900	700 " + 300 "	2291	1255	200 " + 800 "	2930	1610
Fine Ag	1749	954	600 " + 400 "	2408	1320	150 " + 850 "	3002	1650
400 Ag + 600 Au	1868	1020	550 " + 450 "	2464	1350	100 " + 900 "	3074	1690
Fine Au........	1967	1075	500 " + 500 "	2525	1385	50 " + 950 "	3146	1730
950 Au + 50 Pt..	2012	1100	450 " + 550 "	2588	1420	Pt pure........	3227	1775

According to the latest investigations of Violle, Barus, Hollborn, and Wien (Ann. Phys. u. Chem. 1895, p. 276) melting-points vary as follows:

F.°		C.°		F.°		C.°	
	Av.		Av.		Av.		Av.
Ag from 1743 to 1802	1772	954 to 986	970	Ni from 2689 to 2762	2725	1476 to 1517	1496
Au " 1912 to 1999	1956	1045 to 1093	1069	Pd " 2732 to 2989	2861	1500 to 1643	1572
Cu " 1929 to 2006	1969	1054 to 1097	1076	Pt " 3194 to 3371	3283	1757 to 1855	1806

306. Seeger's Cones are furnished by the Chemical Laboratory for Clay Industry, Kruppstr.

6, Berlin, N.W., which are used especially for determination of high furnace temperatures and have been used especially in testing materials for comparative determination of fire-resistance of fire-proof materials. The cones are triangular pyramids of various mixtures of fire-resisting materials which undergo deformations at high temperatures, as shown in Fig. 207, or melt completely. The cones are numbered from No. 022 to 36, and their melting-points are nominally between 1094° F. (590° C.) and 3362° F. (1850° C.). According to reports of Dr. Hecht (*L 169*):

Cone No. 022 melts at about (average)	1094° F.	590° C.
" " 010 " " " "	1742° "	950° "
" " 1 " " " "	2102° "	1150° "
" " 10 " " " "	2426° "	1330° "

With these determinations as a base Dr. Hecht estimates the melting-points of the complete series at the temperatures given in Table 25.

Table 25.—Melting-points of Seeger's Cones, estimated by Dr. Hecht.

(Thon-Ind. Ztg. 1896, p. 294.)

	F.°	C.°		F.°	C.°		F.°	C.°
No. 022	1094	590	No. 02	2030	1110	No. 18	2714	1490
" 021	1148	620	" 01	2066	1130	" 19	2750	1510
" 020	1202	650	" 1	2102	1150	" 20	2786	1530
" 019	1256	680	" 2	2138	1170	" 21	2822	1550
" 018	1310	710	" 3	2174	1190	" 22	2858	1570
" 017	1372	740	" 4	2210	1210	" 23	2894	1590
" 016	1418	770	" 5	2246	1230	" 24	2930	1610
" 015	1472	800	" 6	2282	1250	" 25	2966	1630
" 014	1526	830	" 7	2318	1270	" 26	3002	1650
" 013	1580	860	" 8	2354	1290	" 27	3038	1670
" 012	1634	890	" 9	2390	1310	" 28	3074	1690
" 011	1688	920	" 10	2426	1330	" 29	3110	1710
" 010	1742	950	" 11	2462	1350	" 30	3146	1730
" 09	1778	970	" 12	2498	1370	" 31	3182	1750
" 08	1814	990	" 13	2534	1390	" 32	3218	1770
" 07	1850	1010	" 14	2570	1410	" 33	3254	1790
" 06	1886	1030	" 15	2606	1430	" 34	3290	1810
" 05	1922	1050	" 16	2642	1450	" 35	3326	1830
" 04	1958	1070	" 17	2678	1470	" 36	3362	1850
" 03	1992	1090						

307. Of the more modern pyrometers for measuring high temperatures I shall here mention only those of Siemens, Le Chatelier, Callendar, Wiborgh (*L* 170, 171) and Uehling.* The Le Chatelier has been found to be especially satisfactory, and has been largely introduced in industrial shops because of its easy manipulation and wide scope. It must be here added that the Uehling is finding a much more rapid and general introduction, especially in the United States, because it is automatic as well as autographic, and requires no attention once it is started. It has also been found to be more constant than the Le Chatelier, because the electric couple used in the latter is very changeable during continuous use. The two latter are especially valuable for purposes of tests of materials, because the thermo-electric couple in one case and the platinum tube in the other can be readily inserted into every apparatus, and frequently be brought in direct contact with the test-piece the temperature of which is to be determined. The thermo-electric couple of the Le Chatelier, formed by twisting a platinum and a platinum-rhodium wire together, measures the temperature by use of a Deprez-d'Arsonval galvanometer, the amplitudes of which are proportional to temperature to which the thermo-electric couple is exposed.

These instruments, especially the thermo-electric couple used therein, are also calibrated upon request by the Imperial Physico-Chemical Institute and certified; this is certainly desirable if reliability of results is a consideration.

According to the experience of the Imperial Institute and of other investigators, even very high temperatures, such as the melting-points of iron, may be determined accurately to a few degrees.

The type of instrument made by Keiser & Schmidt of Berlin (*L 172*) is portable and exceedingly convenient.

* Added by the translator; also see statements relating thereto (*308a*).

The readings are observed on a scale which is divided not only in volts, but also in C.° according to the calibration of the Imperial Institute. The readings run from atmospheric temperatures to 2668° F. (1500° C.), and can be estimated to single degrees; these instruments should also be calibrated before use.

308. For scientific and industrial purposes it is convenient that the instruments be autographic. Roberts-Austen devised a pretty photographic recorder (*L 171*). In this instrument rays of light are reflected from a galvanometer, having a revolving and a fixed mirror contained in a dark chamber, through a narrow slit on to the sensitive paper mounted on a clock-driven drum; this produces a curve and a base-line, the ordinates between the two representing a measure of temperature. The instrument is arranged in such manner that the temperatures existing in furnaces located at different points can be recorded intermittently.

308a. The Uehling Pyrometer is used in exactly the same manner, except that the record is in ink, always visible, and can also be interrupted to control a number of furnaces at the same time; its readings run from atmospheric temperatures to those just below the melting-point of platinum; anything approaching this point would endanger the platinum tubes which are inserted in the heat to be determined.

The Pneumatic Pyrometer is based on the laws governing the flow of air through small apertures.

If two such apertures A and B, Fig. 207a, respectively form the inlet and outlet openings of a chamber C, and a uniform suction is created in the chamber C' by the aspirator D, the action will be as follows:

Air will be drawn through the aperture B into the chamber C', creating suction in chamber C, which in turn causes air from the atmosphere to flow in through the aperture A. The velocity with which the air enters through A depends on the suction in the chamber C, and the velocity at which it flows out

through B depends upon the excess of suction in C' over that existing in the chamber C, that is, the effective suction in C'. As the suction in C increases, the effective suction must decrease, and hence the velocity at which air flows in through the aperture A increases, and the velocity at which air flows out through the aperture B decreases, until the same quantity of air enters at A as passes out at B. As soon as this occurs no further change of suction can take place in the chamber C.

Air is very materially expanded by heat. Therefore the higher the temperature of the air the greater the volume, and the smaller will be the quantity of air drawn through a given aperture by the same suction. Now if the air, as it passes through the aperture A, is heated, but again cooled to a lower fixed temperature before it passes through the aperture B, less air will enter through the aperture A than is drawn out through the aperture B. Hence the suction in C must increase and the effective suction in C' must decrease, and in consequence the velocity of the air through A will increase and the velocity of the air through B will decrease, until the same quantity of air again flows through both apertures. Thus every change of temperature in the air entering through the aperture A will cause a corresponding change of suction in the chamber C. If two manometer tubes p and q, Fig. 207a, communicate respectively with the chambers C and C', the column in tube q will indicate the constant suction in C' and the column in tube p will indicate the suction in the chamber C, which suction is a true measure of the temperature of the air entering through the aperture A.

308b. The Uehling Pyrometer. The practical application of the above principle to the measurement of heat up to 3000° F. is illustrated in Fig. 207b. The aperture A is located at the end of a small platinum tube, placed within a larger tube of the same material, closed at the end A (Fig. 207b), and is called the fire-tube. The aperture B is

located within the pot G (Fig. 207b), kept at a uniform temperature of 212° by the exhaust-steam of the aspirator D.

The chamber C is composed of the pipe connecting the apertures A and B, together with the branches q and s leading respectively to the manometer q and a recording-gauge.

The suction is regulated by a water-column in the vessel H, and the air-space above the water in H constitutes the chamber C', which connects with the aspirator D through the pipe m and the chamber C through the pipe l.

The temperature-scale is placed between the manometer-tubes q and p, so that it is in plain view, and the heat may be read off to within 5° up to 1500° Fahrenheit, at a glance, and to within 10° to 2500°.

The pipe gg is made of drawn copper tubing and may vary in length from a few feet to several hundred feet, so that the regulator H with the temperature-scale and the recording-gauge may be set in any safe and convenient place, within a reasonable distance from the furnace or other space the temperature of which is to be measured.

I is a chamber filled with cotton, through which the air is filtered and freed from dust, etc., to prevent clogging the apertures.

i. Repetitive Tests.

1. In General.

309. The name of "Repetitive Tests"* (Dauer-

* Heretofore the word "Dauerversuche" has been translated into "fatigue-tests," "endurance-tests," "durability-tests," continuous tests" and "repetition of stress," and while the latter is somewhat descriptive it is not a convenient term or precise word.

The other terms are absolutely incorrect, because the terms used refer either to what happens to the material or to an incorrect conception. The correct name is "repetitive tests," tests in which loads are applied repeatedly regardless of what happens to the material during the tests. This term is self-explanatory. The object of the tests is not to find the loads or number of repetitions thereof which will fatigue the material, but precisely the reverse, i.e., the number of repetitions of stress which the material can resist without fatigue.—G. C. Hg.

versuche) is applied to all those strength-tests in which the material is relatively stressed but lightly, the same stress being frequently repeated or applied. These tests imitate to a certain degree the actual conditions of service of details of construction. Their results form the basis for the views at present held in regard to limit of stress permissible in construction, and hence it is necessary that the kind and methods of repetitive tests, as well as the essential data thus far derived therefrom, be here briefly referred to; a more complete presentation of the subjects devolves upon the study of construction.

310. Although others had been engaged on tests which should be counted among the "Repetitive Tests," it is customary to name Woehler as their originator (*L 174*), after whom they are frequently called "Woehler's Tests." Even Woehler's designs of repetitive-test machines have been adopted by several other investigators, and those used by himself have been preserved and are now employed at the Charlottenburg Laboratory for the continuation of the tests commenced by him. Among his predecessors I shall refer to Albert, who made repetitive tests of hoisting-chain (*L 176*) as early as 1829, and Wm. Fairbairn, who reported upon repetitive tests of girders in 1864 (*L 177*). Recently Woehler's tests have been much extended, and several laboratories in the United States are particularly occupied with them. Woehler's tests were thoroughly supplemented by Bauschinger; his work shall here be specially discussed.

311. According to the kind of stress produced by the loads applied, repetitive tests are defined as tension-, transverse-, universal-transverse-, torsional-, alternate-tension-, crushing-, impact-tension-, impact-crushing-, impact-transverse-, impact-torsional-, repetitive .....- tests, etc., etc.

312. The results of all these tests is this: "Any such

stress will produce rupture of the test-piece after a very great number of repetitions thereof, only in case the stress invariably applied (hereafter called initial stress S_A) exceeds a certain amount characteristic of each material. This limiting stress was called the factor of resilience (Arbeitsfestigkeit σ_N) by Launhardt.

2. Variability of Proportional Limit and of Yield-point.

313. Since the time that tests were made with some degree of accuracy, it has been a known fact that application of stress beyond a certain limit produces modification of properties of material. The modifications relate especially to the position of "Proportional Limit" and "Yield-point." When briefly discussing the phenomena of residuary stress, it was demonstrated that material does not immediately return to a condition of rest after a change of stress, and does not at once assume the condition of equilibrium due to this new stress (*53*), and that it required the lapse of minutes, days, months and years before changes of length ceased.

314. The phenomena now to be discussed are of a similar nature. Bauschinger (*L 111, 178*) in his reports of tests of wrought iron, low steel (Flusseisen) and other metals has noted and illustrated them in a manner especially appropriate for our purposes. Earlier as well as more recent investigators have also collected and reported upon similar experiments. Bauschinger's tests shall here be discussed, primarily because they are particularly suitable to elucidate Woehler's earlier determinations. I should at once emphasize that the following conclusions enunciated by Bauschinger must not be generalized, but are empirical deductions limited strictly to the materials from which they were deduced, although the probability exists that they apply to other materials.

a. If forces producing tension be applied to bodies which, beginning at o produce increasing stress until the proportional limit is exceeded, this limit will be modified, provided the material is not already in a condition which has been produced artificially. If the material be again loaded immediately after release, and the new *P*-limit be determined, it will be found at a point higher than the original *P*-limit. If the stress be gradually increased, under repetitive test, beyond that producing exaltation, a further exaltation of *P*-limit will be produced, up to the instant at which the *Y*-point is reached or slightly surpassed.*

If the stress at original proportional limit and yield-point be designated by S_{PO} and S_{YO}, and as a further precision indicating the initial stress, that stress which will exalt them, by S_A, and making the fundamental assumption for all of the following considerations that the initial limits of the material are characteristic of it in its natural state, hence that they have not been in any manner modified artificially heretofore, then a diagram of the law just stated can be plotted.

Graphical representation shall also be resorted to for the elucidation of the following laws, and like occurrences shall be plotted in like manner. The kind of stress (initial stress) is indicated by broken-dotted arrows, the modifications of *P*-limit by fine and those of *Y*-point by heavy arrows. The changes of *P*-limit and *Y*-point due to tension stress are indicated by full, those due to crushing stress by dotted, lines. Stress is plotted upwardly with reference to axis of X for tension, and downwardly for crushing.

*From these facts the conclusion, very important under certain conditions in testing materials, may be drawn: that release of load within the *P*-limit is not permissible when the determination of the latter is one of the objects of the test. There are still other reasons which make the release of load during the test seem inadmissible under certain conditions.

Under these assumptions the law stated above under *a* is plotted in Fig. 208 up to the limit *a*.

b. Under increasing initial stress (part *a*, Fig. 208) the *P*-limit rises up to a maximum, and at the instant of reaching the original *Y*-limit (Y_u) the *P*-limit decreases quite materially. If the *Y*-point be greatly exceeded, the *P*-limit may drop to 0 (part *b*, Fig. 208).

c. If the bar remain quiescent after application of stress, the *P*-limit will rise in course of time, rapidly at first, then more slowly; it may rise beyond the original *Y*-point in course of years, and occasionally even beyond the preceding initial load (part *c*, Fig. 208).

d. By applying an initial stress greater than that at the original *Y*-point, the latter is also raised, and in fact immediately after loading. When at rest after release the *Y*-limit will in course of time rise above the initial stress (part *d*, Fig. 208). This rise is plainly visible even after one day, but continues for weeks, months and years.

e. Applying initial stress beyond the original *Y*-point also lowers the modulus of elasticity $E = \frac{1}{e_f}$ (i.e., the factor of elongation is increased), Fig. 209. When at rest after release, the modulus of elasticity again increases, but more slowly than the *P*-limit. After several years it will be found to have risen considerably above its original value. (N.B.—Bauschinger gives several exceptions.)

f. If the *P*-limit and *Y*-point have been raised by rest after release from initial stress greater than that at these points, severe jarring, such as is produced by cold ham-

mering, will again lower the P-limit and Y-point, Fig. 210. The P-limit will return quite to its original value, if hammering has not produced extension of the bar (*b* Fig. 210). But if hammering has produced extension the P-limit will drop slightly, but not to its original value* (*c*, Fig. 210).

g. If the P-limit and Y-point have been raised by rest after release, high heating will again depress these points, Fig. 211. The method of cooling plays an important part in this case, because rapid cooling of a heated bar acts more effectively than slow cooling. The effect of heating iron [in Fig. 211, F refers to low steel (Flusseisen) and S to wrought iron] does not begin below 662° F. (350° C.). Even tenfold heating below this point does not produce any change of the P-limit. The change becomes noticeable in low steel (Flusseisen) at 662° F. (350° C.) if cooling occurs rapidly (full arrows), and at 842° F. (450° C.) when cooling slowly (dotted arrows). In case of wrought iron both actions commence at 752° F. (400° C.). Depression of P-limit and of Y-point was greater under higher heating; it is more active at the P-limit than at Y-point (Bauschinger gives exceptions to this rule). Heating to 932° F. (500° C.), but positively to cherry-red heat (*k*, Fig. 211), causes the P-limit almost to vanish, or entirely so,† and in case of wrought iron as well as in low steel (Flusseisen). Slow cooling even after previous application of red heat does not produce such great depression of the P-limit.

The time of repose after heating and cool-

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* It is difficult to understand this when it is recalled that extension by hammering must have the same effect as though produced by tensile stress. Hence, according to law *b*, a markedly depressing effect should occur. It is deemed advisable to bestow further study on this point.

† It would be of interest to determine whether vibrations (tremor) could again augment such a depressed P-limit, for, evidently, it does not possess its correct value. Similarly it should be determined whether powerful electric or magnetic excitation could modify artificially altered P limits and Y-points.

ing has no further effect upon the P-limit and Y-point depressed by heating.

h. If initial stress between limits O and $+ S$ be oft repeated (oscillations of initial stress between O and $+ S$), and if S remains between the original P-limit and Y-point, the P-limit in course of time will be raised even to, and in fact sometimes materially above, the initial stress, and beyond the original Y-point, Fig. 212. This augmentation is greater as the number of oscillations increases, without, however, being able to exceed a certain maximum. (Bauschinger mentions exceptions thereto.)

i. If the upper limit of vibrations be raised, the P-limit cannot ultimately be raised to the maximum of initial stress, even by a very great number of repetitions, Fig. 213.

k. If the augmented P-limit may even exceed the limit of initial stress, a very great number of repetitions (several millions) will not produce rupture. If, however, the maximum initial stress exceeds the attainable maximum of the P-limit, rupture must occur after a limited number of repetitions.

l. Maximum stress S_M is not depressed, but rather raised, by million-fold repetition of initial stress, if the bars be ruptured by steady load thereafter.

Unfortunately Bauschinger's tests do not enable us to deduce facts relating to modification of deformability $e\%$ and $c\%$ with sufficient definition. From general technical experience we may, however, conclude that deformability is gradually exhausted by oft-repeated initial stress, if the initial stress exceeds the values indicated in law k. Further investi-

gations of this question would be of great interest, especially if it were determined to which degree $e\%$ and $c\%$ would become modified under conditions stated in *h* and *i*.

Thus far the effects on *P*-limit, *Y*-point, and maximum stress for tension produced by initial tensional stress have been considered. These tensional initial stresses, however, also affect the *P*-limit and the *Y*-point for crushing-stress. The crushing initial stress, on the other hand, also affects the $+P$-limit and $+Y$-point for tension. The laws governing these effects are the following:

m. Initial stress greater than the original $+P$-limit depresses the original $-P$-limit, and more largely as the initial stress is greater, Fig. 214. Even relatively slight transgression of the $+P$-limit depresses the $-P$-limit to 0.

Initial stress above the original $-P$-limit likewise depresses the $+P$-limit to 0.

n. If initial stress, alternately tension and crushing, in reverse sense increase the $-P$- and the $+P$-limits (corresponding to law *a.*), and then transgress them, the *P*-limit for the reverse initial stress will immediately be depressed to 0, Fig. 215.

The time of repose after release has no, or at most slight, effect under these conditions, i.e., the *P*-limits for tension and crushing, depressed by opposite initial stress, certainly does not recover within at least 3 or 4 days, nor in the next few weeks, or but slightly, Fig. 221.

o. A *P*-limit depressed by a contrary initial stress greater than the original *P*-limit may again be exalted by gradually increasing alternate tension-crushing initial stress, but only to

a point which is considerably lower than the relative original P-limit, Fig. 216.*

p. Gradually increasing, alternate tension-crushing, initial stress can produce depression of the P-limit for contrary stress only if the initial stress exceeds the original P-limit, Fig. 217.

q. If the exaltation of yield-point is dependent upon the value of previously applied initial stress (laws *a* and *b*), it might be supposed that this exaltation would vary in different parts of a bar subject to tension-stress. And in fact this exaltation ought to be greater at the middle than at the ends, at the gorge than at parts uniformly reduced, if the bar be ruptured by repetition of initial stress, with intermittent periods of rest; i.e., the shape of diagram of deformations (*133*) must be changed.

r. To test the accuracy of this surmise, I had five cylindrical test-pieces of 0.8 in. (2.0 cm) diam. prepared from a bar of low steel (Flusseisen) of $l = 12.5\sqrt{a}$, and tested in such manner that the bars were first loaded to produce stress $= S_M$. Then the elongations of length divisions ($l = 0.565\sqrt{a}$) were measured, and thereupon, after different periods of rest, again loaded until they began to extend anew, measured and the process repeated; the tests were made with use of the autographic recorder of the machine. Although the diagrams thus obtained do not show the true elongation of the test-bars (the motion of the drum being derived from parts of the machine), they nevertheless give a more rapid and more readily comprehensible view than tables of figures; they are therefore grouped in Fig. 218.

To the first diagram, which represents the behavior of the material in its original condition of each bar, are added the

* It may be surmised that tremor (shock) and annealing act similarly, but it should be confirmed by test.

Table 25. Effect of Repeated Elongation and Repose on the Dia

No. of Divisions.	Elongation of Individual Divisions																	
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
	Bar No. 1. $a = 3.15$ sq. cm; $S_Y = 3270$ at.									**Bar No. 2.** $a = 3.17$ sq. cm; $S_Y = 3860$ at.								
0–1	14	15	15	15	15	16	15	15	15	15	16	18	18	18	18	18	18	17
1–2	16	15	15	16	16	16	17	17	18	19	19	18	18	19	19	19	19	18
2–3	17	20	20	20	21	21	21	22	20	19	20	20	20	20	20	20	20	20
3–4	17	17	18	19	20	19	19	18	19	19	19	19	19	19	19	19	19	18
4–5	19	20	19	20	20	20	22	22	22	17	16	17	17	18	18	18	18	19
5–6	19	19	20	21	20	21	21	21	21	17	17	18	18	17	17	17	17	18
6–7	19	20	21	20	23	22	22	22	22	17	18	19	19	18	18	18	18	17
7–8	21	22	22	24	23	25	23	23	23	18	18	17	18	19	19	19	19	19
8–9	21	22	23	24	24	24	26	26	26	19	19	20	19	20	20	21	21	20
9–10	20	23	23	25	26	26	26	26	26	22	23	24	24	22	22	21	21	23
10–11	21	23	24	24	25	26	25	26	26	23	22	25	25	28	30	30	30	28
11–12	22	22	23	24	24	24	24	25	25	25	25	25	27	29	28	29	29	30
12–13	20	22	21	23	25	24	26	25	25	22	24	25	27	27	29	28	28	28
13–14	21	22	24	27	25	26	24	27	27	23	26	25	27	26	26	27	27	27
14–15	21	23	25	24	29	30	31	30	30	23	25	25	25	26	25	24	26	27
15–16	22	22	24	27	30	33	38	45	58	22	24	25	26	27	30	31	31	32
16–17	21	23	26	27	29	35	35	44	77	23	25	16	28	30	32	34	43	78
17–18	21	22	25	26	28	27	33	30	30	24	24	25	28	28	30	33	36	43
18–19	20	21	21	21	23	26	22	30	24	20	19	24	24	24	26	24	26	23
19–20	17	19	18	20	20	20	19	20	20	19	19	20	20	21	20	21	21	25
Mean Differences.	19.5 19.5	20.6 1.1	21.4 0.8	22.4 1.0	23.3 0.9	24.1 0.8	24.5 0.4	25.7 1.2	27.7 2.0	20.3 20.3	21.4 1.1	21.8 0.4	22.4 0.6	22.8 0.4	23.3 0.5	23.6 0.3	24.4 0.8	26.5 2.1
Time: Minutes	0	30	70	90	100	110	130	160	165	—	—	—	—	—	—	—	—	—
Days	—	—	—	—	—	—	—	—	—	0	1	2	3	4	5	7	8	9
Repose: (Min.) Days	(0)	(30)	(40)	(20)	(10)	(10)	(20)	(30)	(5)	0	1	1	1	1	1	2	1	1
Smallest a_1 sq. cm	2.61	2.57	2.54	2.50	2.43	2.35	2.27	2.06	1.47	2.60	2.57	2.54	2.51	2.49	2.45	2.40	2.32	2.29
$S = \frac{L}{a}$. at.	5490	5500	5505	5510	5500	5490	5420	5400	5120	5610	5650	5620	5640	5610	5520	5560	5500	5340
$S_1 = \frac{L}{a_1}$. at.	6630	6750	6820	6940	7120	7360	7550	8260	11000	6830	6980	7010	7110	7120	7150	7320	7520	7410
	$e\%_{5\cdot8} = 34.0\%$; $e\%_{11\cdot3} = 29.5\%$; $c = 54\%$; $S_M = 5510$ at.; $S_R = 5120$ at.									$e\%_{5\cdot6} = 33.6\%$; $e\%_{10\cdot1} = 29.0\%$; $c = 43\%$; $S_M = 5650$ at.; $S_R = 5340$ at.								

diagrams obtained during each repetition of stress. The periods of rest were the shortest possible in No. 1; in bar No. 2 they were one day; in bar No. 3, originally one week; unfortunately, change of assistants and pressure of work caused a greater interruption which made its disturbing effect noticeable. For bar No. 4 a period of rest of one month, and for No. 5 of six months had been contemplated. These arrangements could not, however, be adhered to, as is shown by Table 25, which also contains the changes of yield-points, referred to the

gram of Elongation of Standard Rounds of Low Steels (Flusseisen).

in $e\%.10^{-2}$ according to Test No.

1	2	3	4	5	6	10	15	20	1	2	3	4	5	6	8	1	2	3
Bar No. 3. $a = 3.16$ sq. cm; $S_Y = 3750$ at.									**Bar No. 4.** $a = 3.17$ sq. cm; $S_Y = 3680$ at.							**Bar No. 5.** $a = 3.17$ sq. cm; $S_Y = 3650$ at.		
16	16	16	16	16	16	16	17	17	16	17	17	17	17	18	18	17	17	17
19	19	19	19	19	19	19	19	19	21	20	20	20	20	20	20	20	19	18
20	20	20	20	20	20	20	19	19	22	23	22	22	23	22	22	21	23	23
20	20	20	20	20	20	20	21	22	22	20	23	23	23	22	23	27	26	26
22	22	23	23	23	23	23	23	22	22	24	22	22	22	23	22	31	31	33
23	25	25	25	25	24	25	26	25	21	20	20	20	21	20	21	31	32	31
25	26	33	33	35	39	40	44	46	20	21	20	20	20	21	20	25	25	25
25	26	34	37	38	41	44	50	58	19	19	20	20	20	20	20	21	22	22
24	26	28	27	28	29	28	29	28	20	19	20	20	21	20	20	20	20	20
22	23	24	25	23	24	24	24	24	20	20	20	20	20	20	20	20	20	20
24	24	23	22	23	23	22	22	23	24	21	22	22	21	22	22	19	18	19
20	21	22	21	23	22	23	23	23	21	24	22	23	22	22	22	20	19	18
22	22	20	22	21	21	22	21	21	22	22	23	23	24	23	23	18	18	19
22	21	23	21	21	21	22	21	21	27	27	27	26	24	25	25	20	20	20
21	21	21	21	21	21	21	21	21	26	30	30	30	32	31	33	19	18	19
20	20	20	21	20	20	20	20	20	27	30	31	31	30	32	40	19	20	19
21	21	19	22	21	20	21	20	21	24	26	26	27	27	28	33	17	17	18
20	21	20	20	20	20	21	20	20	22	22	23	22	23	23	24	16	18	18
20	19	20	20	20	21	21	22	21	20	21	20	21	21	20	19	17	18	16
20	20	20	20	20	19	20	19	19	18	17	18	18	17	16	17	17	15	17
21.3	21.7	22.5	22.8	22.9	23.2	23.6	24.1	24.5	21.7	22.2	22.3	22.4	22.4	22.4	23.2	20.8	20.8	20.9
21.3	0.4	0.8	0.3	0.1	0.3	0.6	0.5	0.4	21.7	0.5	0.1	0.1	0.0	0.0	0.8	20.8	0.0	0.1
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0	7	14	21	28	35	368*	403	438	0	30	342	372	403	433	493	0	244	344
0	7	7	7	7	7	333	5×7	5×7	0	30	312	30	31	30	60	0	244	100
2.56	2.53	2.43	2.41	2.41	2.41	2.06	1.87	1.69	2.53	2.51	2.49	2.46	2.37	2.37	2.17	2.48	2.49	2.45
5490	5630	5880	5730	5610	5620	5710	5350	5200	5450	5960	6130	6070	6060	6060	5630	5450	5970	6000
6770	7020	7610	7510	7360	7380	8800	9100	9700	6820	7510	7820	7840	8140	8140	8300	6950	7600	7780
$e\%_{5\cdot 3} = 29.0\%$; $e\%_{11\cdot 3} = 24.6\%$; $c = 46\%$; $S_M = 5880$ at.; $S_R = 5200$ at.									$e\%_{5\cdot 6} = -\%$; $e\%_{11\cdot 3} = -\%$; $c = -\%$.							$e_{5\cdot 6} = -\%$; $c = -\%$; $e\%_{11\cdot 3} = -\%$.		

* Between tests 6 and 7 there was an interval of 321 days.

original, and to the smallest section found in each case just previous to again applying initial stress.

s. From diagrams in Fig. 218 it will be seen that the effect of repose on exaltation of the *Y*-point is plainly visible, is marked in No. 3 (one week's repose), and is more strongly recorded in Nos. 4 and 5. This exaltation is, however, most noticeable in later tests of Nos. 3, 4, and 5, made after greater periods of rest*—a confirmation of Bauschinger's law

* The results could be plotted in the diagrams only as isolated points,

d (*314*). The first section of the law, viz., that the *Y*-point is immediately exalted nearly to the value of the previous stress, agrees with daily experience of most materials; it can be directly verified in diagrams of bars Nos. 1 and 2. The groups of curves especially in case of No. 1 are hardly different from the curve which would have been obtained during a continuous test without intermittent repose. Bars Nos. 3 to 5, on the other hand, show characteristic exaltation beyond the stress previously applied.

t. Still referring to the diagrams, attention is called to the short extension of the curves during individual repetition of stress. While these short lines in case of bars Nos. 1 and 2 follow the general curve up to rupture obtained without release very closely (in contradistinction to the longer parts of curves up to the new *Y*-points), the repetitions, especially of bars Nos. 4 and 5, show an immediate drop of the line after reaching the new *Y*-point. This might have been due to the method of test (the tests were made on the 50-ton Pohlmeyer machine), or the character of the first *Y*-point of the material repeatedly developed and very clearly shown in Nos. 2 to 5. When testing very slowly, to avoid as much as possible the effect of inertia of masses of the weighing apparatus, the line frequently drops suddenly, as shown in Fig. 219 on a larger scale for different cases, then usually showing continued rapid yield after several oscillations of the beam, which is characteristic for many kinds of iron, until regular rise of curve again takes place. The oscillations as shown at *a* indicate oscillations of pendulum about its position of equilibrium which it would assume if the drop did not occur so suddenly. At *b* the curve for the latter case is shown.

Now that greater attention has recently been paid to this phenomenon at the *Y*-point,* it may be important to ask

because the new *Y*-point and permanent extension alone could be determined after test.

* Discussions of various allotropic conditions of iron were based thereon (Osmond and others).

whether the rapid drop following exalted *Y*-point is similar to the phenomenon at *Y*-point in original condition of material? I shall recur to this point.

u. In order to test the previous question (*q*), I plotted the diagrams of elongation (which are to be discussed at greater length elsewhere) for each test individually, and plotted the curve of averages as conforming as closely as possible to individual curves. The curves of elongation were then grouped in Fig. 220.* These diagrams indicate, what must still, however, be verified by a great number of tests of other material, that

> "all parts of the entire bar when tested in original condition, i.e., repeatedly without intermittent repose, under initial stress, take part in the increment of elongation, but that the major part thereof occurs at that part which has been most largely strained during the first application of load."

The shape of the curves shows plainly how contraction takes place. In bar 2 the lines lie closer together from the beginning, but a second contraction has also taken place in tests 6–9 to the left of the principal point of contraction, and at a point which also extended considerably even at the beginning of the test. The curves in 3 to 5 are essentially coincident, only that increased extension, due to repetition of stress, occurs at the point of greatest initial extension. In these tests the divisional extensions produced by repetition of initial stress has been taken smaller than in the previous cases, so that further deductions must not be made from the striking differences.

I hope that these unanswered questions will be further studied by others.

v. Later tests of determinations of elastic behavior of materials, such as those of Bach (*L 112, 136, 137*), Hartig (*L 179, 180*), Martens (*L 107, 109, 157*), and others, have undoubtedly demonstrated that changes of condition of mate-

* Similar diagrams were recently drawn by Pralon (*L 102*, Vol. III. p. 77–101).

rials take place under every application of load, but determinable only by sufficiently accurate measuring instruments. If material be repeatedly stressed and released consecutively, the readings usually vary during each change between the two limits of stress. After a definite number of repetitions they assume a definite value, as the permanent deformation becomes less and less after each release, until finally elastic deformation is alone produced. Deformations for unit of stress $\left(\frac{\Delta e}{\Delta S}\right)$, factors of extension, of deflection, etc., calculated from the deformations in ultimate condition of perfect elasticity, are not usually constant values. They vary in many cases rather with the magnitude of the limits of initial stress producing them.

As it will be necessary to devote greater attention to these facts in future, I here desire to reproduce in Table 26 the results of tests of leather belts, referring at the same time to the publications previously quoted, as made by my students in their regular course of studies. These tests are plotted in Fig. 221. Particular attention is called to Bach (*L 137, 182*) because of the importance of these results on questions relating to leather-belt transmission.

The tests were made on a piece of leather which had 560 days previously been once tested to rupture. The sample of leather, size (0.8 × 10.0 = 8.00 sq. cm) 0.312 × 3.9 in. = 1.217 sq. in. and weight of $\frac{1}{2}$ lb. per ft. (0.75 kg/m), was provided with gauge-marks $l_g = 40$ in. (100 cm) on Dec. 5 and 12, 1896. Tests then gave the results given in Table 26.

The full lines in Fig. 221 relate to the first, the dotted lines to the second, test made after a 7 days' repose. The hatched areas between the fine lines indicate the limits between which deformations under repetitive stress take place. The variation of inclination of these areas, due to increasing stress, and the trend of the two lines a'', indicate the course of variations of the factor of extension e_f for the perfectly elastic condition;

it diminishes with increasing stress, and changes with repetition of test, after previous repose.

Table 26. Tests of the Elastic Properties of a Leather Belt.

S at.	$\epsilon \cdot 10^{-4}$	Differences of Load $\Delta\epsilon''$	Differences of Release $\Delta\epsilon'$	$a'' \cdot 10^{-6} = \frac{\Delta\epsilon''}{\Delta S}$	S at.	$\epsilon \cdot 10^{-4}$	Differences of Load $\Delta\epsilon''$	Differences of Release $\Delta\epsilon'$	$a'' \cdot 10^{-6} = \frac{\Delta\epsilon''}{\Delta S}$	S at.	$\epsilon \cdot 10^{-4}$	Differences of Load $\Delta\epsilon''$	Differences of Release $\Delta\epsilon'$	$a'' \cdot 10^{-6} = \frac{\Delta\epsilon''}{\Delta S}$
Tested Dec. 5, 1896 (after 560 days release).														
5	0	—	—	—	15	132	—	—	—	25	221	—	—	—
15	122	122	—	—	25	215	83	—	—	50	383	162	—	—
5	53	—	69	—	15	169	—	46	—	25	287	—	96	—
15	129	76	—	—	25	218	49	—	—	50	387	100	—	—
5	58	—	71	—	15	172	—	46	—	25	292	—	95	—
15	136	78	—	—	25	220	48	—	—	50	389	97	—	—
5	58	—	78	—	15	173	—	47	—	25	295	—	94	—
15	135	77	—	—	25	221	48	—	—	50	392	97	—	—
5	62	—	73	—	—	—	—	—	—	25	300	—	92	—
15	134	72	—	—	—	—	—	—	—	50	393	93	—	—
5	60	—	74	—	—	—	—	—	—	25	303	—	90	—
15	136	76	—	—	—	—	—	—	—	5	142	161	—	—
5	63	—	73	—	—	—	—	—	—	5*	142	6	—	—
15	136	73	—	—	—	—	—	—	—					
5	66	—	70	—	—	—	—	—	—	* Read after 1 min. delay.				
15	137	71	—	—	—	—	—	—	—					
5	64	—	73	—	—	—	—	—	—					
$\Delta S = 10$ at.; $\Delta\epsilon'' = 73$; $\epsilon' = 64$				730	$\Delta S = 10$ at.; $\Delta\epsilon'' = 47$; $\epsilon' = 41$				470	$\Delta S = 25$ at.; $\Delta\epsilon'' = 93$; $\epsilon' = 82$				372
Tested Dec. 12, 1896 (after 7 days' further repose).														
5	41	—	—	—	15	161	—	—	—	25	251	—	—	—
15	158	117	—	—	25	243	82	—	—	50	403	152	—	—
5	73	—	85	—	15	191	—	52	—	25	303	—	100	—
15	159	86	—	—	25	247	56	—	—	50	407	104	—	—
5	74	—	85	—	15	196	—	51	—	25	309	—	98	—
15	161	87	—	—	25	249	53	—	—	50	412	103	—	—
5	74	—	87	—	15	200	—	49	—	25	309	—	103	—
—	—	—	—	—	25	250	50	—	—	50	411	102	—	—
—	—	—	—	—	15	200	—	50	—	5	134	—	277	—
$\Delta S = 10$ at.; $\Delta\epsilon'' = 86$; $\epsilon' = 33$				860	$\Delta S = 10$ at.; $\Delta\epsilon'' = 51$; $\epsilon' = 39$				510	$\Delta S = 25$ at.; $\Delta\epsilon'' = 103$; $\epsilon' = 58$				412

The well-known and frequently accurately observed modifications which many metals undergo during cold working, such as wire-drawing, cold rolling, hammering, etc., may be classed among the modifications of properties here discussed, because they relate particularly to the elastic limit and yield-point in the cases named.

3. Types and Methods of Woehler's Repetitive Tests.

315. Although the description of machines for repetitive tests shall be reserved for a later section, it will be advisable to here discuss their principles of construction, especially those of the Woehler machines, to facilitate comprehension; later description may then be brief.

In repetitive-test machines the same essential parts may be defined as in other testing-machines (*62*); they shall be similarly designated.

316. For tension loading, Woehler constructed his machine according to principles idealized in Fig. 222. Load-indication is effected by the spring *F* acting on lever *A*, depressing it against the stop *G*. By means of nut *H* any desired tension may be imparted to the spring. Lever *A* is connected to *B* by the cross-head *C*, supported by a vibrator *EJDM*. The lever *B* carries one holder for test-piece *L*, which is held by the frame of machine by the adjustable nut *K*. The machine is driven by a shaft having an eccentric, which reciprocates *M*. The lever *D* transmits this motion by adjustable sleeve *J* and spring *E* to the intermediate cross-head *C*.

Whenever the spring *E* is strained by lever *D*, stress will be produced in *C* which is equal to half-stress in *E*. Adjustment of nut *J* gradually increases, until that part of the force acting on *A* is just able to raise the lever from the support *G*. At this moment this force has precisely that value to which it is to be raised by the spring *F*. The force acting at the other end of *C* has the same value, because the two arms of *C* are equal in length. This force is transmitted, magnified tenfold, by lever *B* to the test-piece, the maximum stress in which is thus regulated by tension of spring *E*.

The lever *D* is attached to *J* by an open link, so that upward motion of *D* after complete release of *E* produces no

inverse stress in that spring. In this case E to a certain degree assumes the functions of a rigid member; the test-piece is acted upon by a change of stress from 0 to that in F for each stroke of D.

If, however, the nut J be so adjusted as to strain the spring E when D is in its initial position, the test-piece L will also be subject to stress in this initial condition; and the variation of stress will take place between definite minimum and maximum limits. The lower limit will also be regulated by the indicating-spring F, as was shown.

317. Woehler constructed his machine for repetitive transverse tests on the same principles. The load-indicator and its method of operation remain the same; test-piece L, Fig. 223, takes the place of lever C. The nut J is adjusted until the lever A just rises from the stop G, under the effect of the power applied at M. The spring F determines the resistance of bearings, and hence the maximum stress in the bar. If the stress is to alternate between definite minimum and maximum values, the desired bearing-resistance at L is produced by first adjusting F to the minimum stress, and then, after producing the desired deflection and stress, N is adjusted so far as to maintain this deflection of bar and prevent release even when lever D is entirely released. Now the spring F is adjusted to the bearing-resistance under maximum stress, and J is adjusted so that the stroke of D just releases the lever A from stop G.

318. In machines (Fig. 224) used for tests by universal transverse stress, Woehler arranged them in such manner that the bar was fixed in a shaft W revolving in bearings A and B, driven by a pulley S. The spring F acting at the free end of the bar L produces the desired transverse stress. All fibres beyond the neutral axis are subjected to alternating tensional and crushing stress during each revolution. In this type of

loading the maximum stress exists only in the dangerous section, at the edge of the grip or holder.

319. Woehler's machine for repetitive torsional stress is based on the following scheme, Fig. 225. It is arranged for right- as well as for left-hand torsional moments, and also for alternation of these. Loads are indicated by springs F and F_1 as before. The test-bar is placed at L normal to the plane of the illustration, having the double arm BB_1, at one end and operated by the lever D at the other. When D oscillates, either N or N_1 act as stops for the ends of levers A and A_1, which are raised from stops G and G_1. This produces a definite torsional moment. If alternating right- and left-hand moments are to be used, screws N and N_1 must be adjusted in such manner that levers A and A_1 are just raised clear of stops G and G_1 by each full stroke of D.

4. Results of Woehler's Tests.

320. Although Bauschinger's laws still require further amplification and proof for their general applicability, they have nevertheless already opened the path of correct knowledge of occurrences during repetitive tests.

According to law k (*314*) it may be expected that a body may bear an infinite number of repetitions of load between 0 and a maximum limit, provided this upper limit be so fixed that the repetition of initial stress may exalt the original P-limit to a value above that of the maximum initial stress.

For the case of alternating tension and crushing stress the laws n and o (*314*) make it seem advisable to gradually increase the upper limit of stress, because otherwise there might be initial excess of stress, the effects of which cannot again be eliminated. Sufficient knowledge in this matter is, however, still lacking, as the phenomena which may be expected to

take place under these conditions cannot be exhaustively identified in Bauschinger's laws.

321. The object of repetitive tests, for various kinds of stress and of all important constructive materials, is to determine that stress by which they will not be ruptured under very numerous repetitions thereof. This stress was called the factor of resilience (*312*) of the material for the particular stress.

Woehler attempted to determine these limits directly by the repetitive test. For this purpose he had bars of identical shape and material prepared, and tested them under varying stress-limits, determining the number n of repetitions of stress which ruptured his bars. The curves constructed from these results of his tests seem to conform to definite laws, and the limiting stresses, i.e., the factors of resilience can be readily derived therefrom. For reasons given in (*310*) it will suffice to state the general character and essential drift of the results; for this I use mainly the series of tests of Woehler and Spangenberg (*L 174*, *175*).

322. Woehler and Spangenberg used bars of shape shown in Fig. 226 for tension-tests (*316*, Fig. 222), the points a being either square shoulders or filleted. In Fig. 227 group a shows the number of repetitions applied sufficient to rupture such a bar by tension when under stress from 0 to S_A. The number of repetitions n of such initial stress S_A increases with decreasing S_A; the average curve of values plotted drops and becomes tangent to the right line S_N, Fig. 228, as an asymptote. This right line represents that stress S_N which no longer produces rupture; i.e., the factor of resilience of any material, under repetitive tension-stress between 0 and $+S_N$

The factor of resilience under tension-stress, under the conditions stated, may be assumed as follows for the materials investigated:

A) Tensile stress, bars with filleted shoulders:

a) Cast steel,	S_N=42660 lbs. per sq. in.	(3000 at.)
b) Wrought iron,	" =28440 " " "	(2000 at.)
c) Cast iron and *d*) Bronze,	" = 8532 " " "	(600 at.)
e) Phosphor Bronze,	" = 9954 " " "	(700 at.*)

323. Similar curves would respresent the number of repetitions of bending-stress between 0 and S_A (*317*, Fig. 223) producing rupture under decreasing stress S_A. The asymptote S_N, in this case, is again found as in Fig. 228.

The factor of resilience under bending-stress, under the conditions stated, may be assumed as follows for the metals investigated:

B) Bending-stress:

a) Cast steel,	S_N = 46900 lbs. per sq. in.	(3300 at.)
b) Wrought iron,	" = 32700 " " "	(2300 at.)
c) Bronze,	" = 11400 " " "	(800 at.)

Similar curves are also obtained for repetitive transverse tests when the bars are simultaneously revolving, producing alternating stresses $+S_A$ and $-S_A$. Under these conditions, when using bars of shape shown in Fig. 229, having either a square corner or a filleted shoulder, the factor of resilience of the materials tested was found to be about:

C) Universal bending, filleted shoulders:

a) Cast steel,	S_N = 25600 lbs. per sq. in.	(1800 at.
b) Wrought iron,	" = 18500 " " "	(1300 at
c) Copper,	" = 11400 " " "	(800 at

324. The same material may be subjected to an initial stress essentially higher if the stress be not allowed to return t

* These values cannot be generalized, especially as the character of materials has totally changed during the last decades and become quite different from that of the bars used by Woehler and Spangenberg.

o, but maintained between a minimum and a maximum. The results of such tests may be represented by curves as in Fig. 230 for bending-stress (*317*, Fig. 223). The curves indicate the number of repetitions s producing rupture of the material when alternately stressed between limits indicated by the ordinates of $S_{A_{max.}}$ and $S_{A_{min.}}$; the abscissa indicates the number of repetitions producing rupture.

If stress-limits which produce rupture of unhardened spring-steel after a million-fold repetition be selected by approximate evaluation from the Woehler-Spangenberg tests, and also those limits which no longer produce rupture, or for which $n = \infty$, the following table may be constructed under the assumptions just stated:

E) Bending-stress between limits.

a. Upper S_A maximum at.	4000	4790	5470	6150	6840
Lower S_A minimum at.	0	1300	2200	3300	4100
For rupture after $n = 1$ million Diff. $S_{max.} - S_{min.}$ at.	4000	3490	3270	2850	2740
b. Lower S_A minimum at. For rupture after $n = \infty$	0	1500	2500	3800	4500
Diff. $S_{max.} - S_{min.}$ at.	3700*	3290	2970	2250	2340

* Upper limit for $S_{min.} = 0$ was $S_{max.} = 3700$ at.

These figures make it apparent that the value of maximum stress is not alone critical for resistance of material subject to repetitive stress, but that the amplitudes or variations of stress are an essential factor. The more the upper limit of initial stress rises the smaller must be the amplitude of stress, if rupture is not to be produced by frequent repetition of stress.

Woehler particularly demonstrated the injurious effect of abrupt changes of shape of constructive details and confirmed all our experience by figures.

Woehler's determinations of effect of unfilleted shoulders are expressed by the following numbers.

He reports the results of [illegible] transverse tests of filleted and unfilleted test-pieces cut from a railway carriage axle [illegible]:

lbs. per sq. in.

a) Wrought iron, filleted bars $S_t =$ [illegible]

b) Wrought iron, square corners $S_t = 14,$[illegible]

The factor of resilience in cases a and b is as 100 : [illegible]

Woehler also demonstrated injurious effect of omission of fillets under effect of tensile stress. He found the number of repetitions of stress producing rupture to be

lbs. per sq. in.

a) Steel, under $S_t = 44,550$ (3130 at.) $n = 1.56$ millions, fillet

$S_t = 29,150$ (2050 at.) $n = x$ – sharp corners

b) Iron, under $S_t = 35,000$ (2460 at.) $n = 0.41$ – fillet

$S_t = 35,000$ (2460 at.) $n = 0.04$ – sharp corners

Or, if the figures compared are granted to have been found under similar conditions, a considerable reduction of safety by square corner is shown.

It is here necessary again to refer to the contradictions of the results previously discussed. We found in (*99–104*) that the effect of sharp corners is to augment the resistance of shouldered bars, and tests of threaded bolts showed an augmentation of nearly 20%. But Woehler's tests demonstrate, what was already well known, that this augmentation of resistance does not in any sense augment the safety of the structural detail which has unfilleted shoulders; on the contrary, the safety at this square shoulder seems to be very

greatly reduced; the degree to which this reduction of safety is carried is sufficiently shown by the figures just given. The cause of decrease of safety seems to me, however, to be identical with that previously assumed in (*100–103*) for increase of resistance. Augmentation of resistance occurs because the deformability of the dangerous section is decreased by sharp corners. Similar causes also decrease the factor of resilience. Deformations (longitudinal and sectional) distribute themselves over a greater mass of material when changes of shape are gradual than when sharp corners are provided; the resilience of the unit of volume at the dangerous section is taxed to a lesser degree in case of gradual changes of shape.

5. More Recent Repetitive Tests.

325. In Woehler's universal repetitive transverse tests described in (*318*, Fig. 224) (bending while revolving) the bar is fully stressed at the dangerous section alone. Hence the modifications of properties of a material, and possibly of its structure due to the resilience, and also those of its physical properties, which might be expected to occur in accordance with Bauschinger's laws (*314*), primarily affect but a very small portion of the bar.

In order to distribute the maximum stress over the greatest possible length of bar uniformly, and thus to secure the possibility of more readily determining the modifications produced in material by repetitive tests, I constructed the machine shown in Fig. 231 for the Charlottenburg Testing Laboratory in 1885 on such a plan that the bar L has the length aa_1, and may revolve in the bearings A and A_1, but can move in its bearings in such manner that the bearings will adjust themselves to the curve of the middle part of the bar. If equal loads F and F_1 be applied at the ends of levers of equal length, Aa and A_1a_1, the entire bar will be subjected to uniform stress while its section remains constant.

All modifications of the material produced by repetitive universal bending-stress must extend over the entire length of bar between A and A_1 uniformly. A subsequent careful

tension-test would therefore make it possible to more readily identify any modifications produced. In order to be able to make a tension-test conveniently and rapidly, that part between A and A_1 is so formed that merely separating the ends a and a_1 will leave a standard cylindrical bar of 0.8 in. diam. (2.0 cm).

A number of adjacent parallel bars are cut from a large rolled billet for a series of test-pieces. One of these bars is placed in the machine, subjected to an excessive initial stress, and driven until rupture is produced. As the factor of resilience can only be determined by test in a most wearisome manner, factors of resilience used were actually estimated for these tests. These estimations were frequently erroneous because of the great differences in character of the material available, and as a result the estimated time necessary for these tests has been greatly exceeded, and they have not yet been completed. This, to my mind, is a proof that repetitive tests must be very largely extended, as the results depend to such a large extent upon the character of the material (*L 110*, p. 136). After producing rupture of the first bar the duplicates are placed in the machine, applying the same stress, $\frac{1}{5}$, $\frac{2}{5}$, $\frac{3}{5}$, and $\frac{4}{5}$ times the number of repetitions which produced rupture. The ends of the bars are then cut off and the middle portion tested in a tension-machine. The results thus obtained are then compared with those obtained from untreated standard bars cut from the same billet. Besides these tests, the material is subjected to microscopical examination, to determine any possible modifications of structure produced by repetitive stress.

326. Repetitive tests, as previously indicated, have also been made in England by Kennedy, and in the United States by Howard at the Watertown Arsenal, and by Lanza at the Massachusetts Institute of Technology at Boston, and others, the latter using a machine very similar to that just described and shown in scheme by Fig. 232. Like parts are lettered as in Fig. 231.

The bar L is stressed through lever B by spring F, and is revolved 500 rev. per min. by a peculiar resilient coupling and a flexible shaft. The load on the spring is produced by the weight G on the lever C; the adjustment by clamps H. It is driven by an electromotor running night and day. The elastic deflections of the bar during repose and when in different positions are measured from time to time.

327. I constructed a machine for the Charlottenburg Testing Laboratory for testing material under alternating tension- and crushing-stress. Its principles are shown in Fig. 233. This machine has been used mainly for wire, braided strands and small rope, to determine the relations between diameters of driving-sheaves and the construction of rope-drives, etc. The wire to be tested is fastened to a lever B at E, which is made to oscillate about the fixed point A by the rod M. The wire loaded by weight G during each vibration of lever B hugs the cheeks C C, which are shaped to curvature of definite radius. Hence the wire is subjected to reverse bending-stress in addition to tension during each vibration. The position of the bending-point A relative to the cheek-pieces C is so chosen that the lateral vibrations of the test-piece become a minimum.

It is the object of the test to determine the number of bends which a wire, a strand, or even a rope under different construction of test-piece may bear in passing around sheaves of definite radius under simultaneous tension-stress. The diameter of rope-sheave must be so chosen that the wear of the rope is a minimum under maximum efficiency of the drive.

328. In (*232*) I have already described another machine constructed by me for the Charlottenburg Testing Laboratory, in which ropes and rope-couplings may be tested under repetitive impact and simultaneous tension.

329. Woehler also made repetitive impact-tests, to determine the effect of impact of wheels on rail-ends at the

joints. In his case a power-driven hammer acted on the heads of rails (*L 157*).

330. A similar machine designed by H. Meyer was exhibited by the Western Ry. of France at the Exposition of 1878 in Paris; it served to test tires mounted on wheel-centres ready for use, by a definite number of blows of a 17½-lb. (8-kg) hammer (*L 183*, p. 39). The management had had more than 6500 tires tested by blows of such a hammer since 1875. 243 tires, or about 2.3%, had thereby been broken, the material of which (Bessemer steel—the material and methods of securing tires at present in use are quite different) was invariably recognized as defective. But very few of the tested tires failed in actual service. This machine, Fig. 234, consists of a spring cushioned hammer *F*, operated by cam *D*, and delivers from 50–60 blows per minute on the tire mounted on its centre *R* revolving slowly in its boxes *L*. The details of construction are given in the reference on Plate VII.

331. Buete (*L 184*) made repetitive tests to determine the serviceability of various methods of securing tires. In these tests the finished wheel-frame was supported in its axle-boxes, and subjected by pressure to bear against disks, which, representing rails, were caused to revolve, so as to obtain speeds used in railway service. The flanges of these disks were not round and provided with interruptions, thus imitating impact, especially lateral impact occurring in regular service. The details of design are given in the reference.

332. Recently, repetitive tests to determine the factor of resilience of compressed gas (CO_2) cylinders under hydraulic

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* The appropriate weight of hammer was determined by a special investigation, discussed in the reference; steel cones were driven into a lead block by hammers of different weight, measuring the factor of penetration in each case, and then the same cones were driven into the lead by drop-weights. The height of drop was varied until equal penetration was produced as found by use of the hand-hammers; thus a measure of impact of hammers of various weights when swung by man was obtained from the work due to impact.

pressure have been inaugurated at the Charlottenburg Testing Laboratory. In these tests, flasks of identical manufacture and material are subjected to pressures of various intensities to determine that initial stress which will no longer produce rupture under very frequent application. The tests shall also decide whether the compulsory repetition of the governmental pressure-test is a cause of danger or a benefit (*L 185*). Very similar tests on a larger scale have been planned for determining the safety of steam-pipes under high pressures and corresponding temperatures.

6. Fractures Produced by Repetitive Tests.

333. As demonstrated in (*324*), rupture in repetitive tests occurs at much lower stress when the bar has sharp corners than when these are filleted. It is, however, a matter of common experience that test-pieces for repetitive tests must be finished very nicely, even polished, if premature rupture should not be produced by any apparently insignificant cause. While marks which may even completely encircle a tension test-piece are very rarely causes of rupture in the ordinary tension-test, great care must be observed in making gauge-marks for the repetitive tension-test if they are not to expedite rupture. Therefore these marks are made as very fine crosses at 45° to the bar-axis at the Charlottenburg Testing Laboratory.

If rupture takes place in the section under these marks, it will invariably be found that the lines of fracture always radiate from these minute defects, which is an indication that these parts actually were the causes of rupture.

The types and phenomena of fractures of repetitive tests are very characteristic, and hence it is possible in a very great majority of cases to state positively whether fracture was pro-

duced by sudden excessive stress of material or whether by frequently repeated slight excess of stress. Plate 2, Figs. 20–23 and 25, shows various fractures produced by repetitive tests. Characteristic properties will be described below.

334. Fracture-lines radiating from a point previously described (*122*, *210*, *276*) are seen in most illustrations, but much more distinctly on the fractured test-pieces themselves. The point of radiation usually lies in the perimeter of the section of bar, which is explicable when considering that in most cases this contains the most highly stressed fibre. [In tension-test (*122*) the point of rupture is origin of radiation; in bending-test (*276*) and in universal bending repetitive test (*318*, *323*) it is still more pronounced; in the torsion-test the position of most highly stressed fibre is dependent upon shape (*L 137*, § 34).]

The point of radiation usually forms the center of an elliptic surface (unless otherwise stated, the following description shall always relate to low steel [Flusseisen]), composed of very fine grain, as indicated in type in Fig. 235, to which is frequently joined the coarser crystalline material showing a clearly defined boundary. This elliptical boundary assumes a circular or rectilinear shape, according to the shape of section, origin of radiation at perimeter, and to the relation between the elliptical surface and total sectional area. The elliptical surface is produced during tension- as well as bending- and torsion-tests, only that it assumes the characteristic forms shown in Plate 2, Figs. 25 and 30, of spirals or meridional lines in the latter cases.

Frequently concentric elliptical bands, with edges almost normal to the lines of fracture, are seen on the elliptical surface. These phenomena lead directly to those of conchoidal fractures, shown by very many materials, which can be very readily studied on vitreous substances.

335. Conchoidal fracture is characterized by undulating elliptic bands, concentric to each other, and frequently arranged in groups, Fig. 236. Coarser or finer rays are noticed running across and normal to these undulations. These rays become

finer and more numerous as the undulations become less pronounced. Glass shows these phenomena in a particularly characteristic manner, and glass splinters, accidentally found, led to the following observations.

The fact that the rays (fracture-lines) on such conchoidal surfaces of such a glass splinter always separate into two branches at the point of radiation whenever they cross the ridge of an elliptical wave can be noted by the naked eye. This branching is repeated at nearly every ridge, and finally the rays become so fine that high microscopic magnification is required to make them visible. The waves are deepest near the point of radiation (origin of fracture); they become more shallow as they recede from it, so that finally they can only be noticed by the shape of reflected rays under the microscope. In the deep waves (near the point of radiation) the rays are confined to the valleys; they only begin to cross the ridges a little further away. Both lower pictures of Fig. 236 show the construction of such radiation, and that the rays are produced by an abruptly and a gradually sloping, almost plane, surface; they retain these peculiarities even when they become microscopical. The angle of inclination of both surfaces appears to be nearly constant; hence both surfaces appear to broaden in the valleys and contract toward the ridges. The phenomena of these conchoidal fractures of glass are of remarkable regularity, and remind one of the regularity of crystallization. The similarity between these phenomena and those described in (*122*, *210*, and *276*), and especially of those of transverse-tests (*276*, Plate 2, Figs. 27 and 28), will be readily recognized.

Fig. 237 shows the fracture obtained by rupture of a nicked steel chisel magnified threefold, in which the limit of granular material is noticeable to a particularly characteristic degree. Fig. 238 shows the branched rays of a fracture of granular material magnified 4 times.

336. Study of fractures produced by repetitive tests easily awakens the surmise that a very radical

change of structure must have occurred during the tests, because the fine velvety structure of the elliptic surfaces is found in abrupt contrast to the coarse, frequently crystalline structure of the remainder of the fracture. Nevertheless it is improbable that essential structural modifications have taken place in the material (*L 186*).

337. If such a fracture (steel), as nearly plane as possible, be ground just sufficiently to remove the surface of fracture, and then polished and etched, microscopical examination of the etched surface will not again reveal the limiting ellipse, which was so marked a feature of the fracture (*L 186*). The structure has not been modified by repetitive stress in such manner that it could at the present time be distinguished by the microscope. Nor did Spangenberg's tests (*L 175*) [which, however, were made by the nicking method described in (*348*)] show any difference of hardness close to the elliptical zone and close to the crystalline part. Bauschinger (*L 2*, Part 13, p. 43) also concludes from his tests and observations that repetitive tests do not modify structure, because in tension-tests even such bars which had already been subjected to very many repetitions of stress nevertheless show all ordinary tension-fractures, while bars of identical material subjected to much more limited repetitions of stress were ruptured, showing all types of repetitive tension-test fractures.

338. In addition to the results previously discussed, the typical illustration of a conchoidal fracture given above for purposes of study warns us to be cautious about drawing conclusions from the appearance of fractures of material. Examination of the unbroken (perfect) glass under polarized light will clearly prove that this exceedingly regular structural arrangement, conforming to a law shown in Fig. 236, does not originally exist in the material. A single sharp blow delivered even to fragments, which thereunder prove themselves absolutely

homogeneous and free from stress, may produce all the phenomena of conchoidal fractures in the shortest period of time, thus proving clearly that this extraordinarily regular arrangement of fracture was produced at the instant of rupture, that it is but a peculiarity of the fractured surface, and that conclusions relating to structural modification of the bar, as a consequence of repetitive stress based on the appearance of the surface of fracture, are not permissible.

339. The question as to whether, and to what degree, any other modification of the properties of materials takes place during repetitive stress can only be decided in the manner previously indicated (*325*) by repeated investigation after application of stress. Bauschinger also pursued this method, and the laws enunciated by him (*i*, 2), as well as his more recent results of tests, admit the surmise that the P-limit, factor of extension e_f, and the S_M and S_R are modified. Unfortunately the effect of repose on the modifications of properties of the materials after straining (law *c*) cannot be eliminated from the results of his repetitive tests, which he interrupted for the purpose of subjecting the bars to repeated straining in order to determine their modifications. These modifications necessarily also proceed in the bar, although in a different degree, even if the bar is not allowed to rest (*53*), but is continuously subjected to the repetitive test.

340. Phenomena of fractures of repetitive tests of non-homogeneous materials, such as wrought iron, are generally characteristic; their enumeration would, however, rather be the subject of a special treatise on repetitive tests in general, or on the properties of definite materials. I merely entered upon the above-described phenomena in such a detailed manner, to again plainly illuminate the internal connection of phenomena of fracture occurring in conformity to laws described in (*117–128, 210, 211, 272–276*).

k. Hardness-tests.

341. The hardness of a matèrial is a property which the constructor frequently utilizes, sometimes valuing it highly, although but rarely attempting to measure it. Technologists have always taken a deep interest in this property, and have frequently attempted to determine it by measurement. Mineralogists regularly determine hardness of their substances. Hence it might be imagined that the conception of hardness had been clearly determined, as far as our practical purposes require, as has been done in the case of resistance, elasticity, etc. But this assumption, even at the present day, is less accurate for hardness and toughness than for any other property of material. Hardness has been compared with all possible properties, and it has hence been attempted to express its value by those of the former. Very much obscurity is found in the bibliography of this subject, as well as strongly contradictory conceptions. Several representations have become so generally adopted that they are frequently used indiscriminately for the same material, according to circumstances, applying sometimes one and again another scale, naturally producing occasional confusion. This condition is solely possible because there is at this time no sufficient and generally recognized definition of this property in use in technology. Nor can I offer one, and hence shall confine myself to discuss the various conceptions and the methods of determination based thereon.

342. The most common definition is:

Hardness* is the resistance opposed by a body to its penetration by another (harder) body.

This definition, in one form or another, is the foundation of most proposed methods for determining hardness.

343. The most generally employed method is that of

* Attention has been called in (5) that there is no opposition between hardness and softness. Therefore the latter will not here be considered. Softness is a lesser degree of hardness, and should therefore be expressed in a similar manner.

mineralogists, by which the relative hardness between a mineral and another used as a standard is determined by scratching one by the other, using sharp edges. This of course only affords a comparison, and a classification of any body among a series of different bodies of different hardness. For the purpose of such classification, so-called scales of hardness, such as the well-known Mohs Scale, have been established, in which well-known minerals, easily obtainable in uniform condition, are arranged after mutual scarification according to their relative hardness, numbering them consecutively.

Mohs' Scale is as follows:

1. Talcum 2. Rock salt (or gypsum)	scratched by finger-nail.
3. Calcspar—	hardness of a copper coin.
4. Fluorspar	a soft ductile iron nail with hardness of 4.5.
5. Apatite	ordinary window-glass has a hardness of 5.5.
6. Orthoclase (felspar) 7. Quartz (flint)	a file has a hardness of 6.5.
8. Topaz 9. Corundum 10. Diamond	scratch glass.
9. Corundum 10. Diamond	cut glass.

A material tested is said to have a hardness of five (5) if it can be scratched by felspar, but will scratch all of the previous materials. Other materials given by Leunis are given in small type.

344. Dumas established a similar scale for metals. But it may be asserted that the mineralogical method of determining hardness leaves us technologists in the lurch, because it is very difficult to establish a scale therefor which furnishes invariable values. For it has been settled that identical minerals of the Mohs scale, but of different provenience, are not of identical hardness, and it is well known that it is very difficult to obtain them absolutely pure, and that their hardness in a pure state

can be changed by the kind and degree of previous mechanical manipulation. Even the slightest chemical difference may, however, produce very considerable difference of hardness. If this were not the case a similar hardness-scale of metals would have been adopted long ago.

345. The hardness of metals is particularly dependent upon chemical composition, and this is the case to an important degree in iron, the hardness and tempering qualities of which are dependent to an extraordinary degree upon the carbon contents Because this fact is emphasized daily in the steel industry, it has become a habit to speak of soft or hard iron (steel) even when mechanical hardness is not under consideration, but chemical composition alone is actually referred to. Iron and steel particularly are said to be soft when they contain a relatively small amount of carbon, or hard when a larger amount is present; it is of course nearly always true that the resistance of iron to deformation during forging, hammering, filing, etc., increases with the carbon, hence that the material richer in carbon appears harder. The foregoing reasons caused the adoption of hardness-scales for tool-steels, arranged according to carbon content.

346. Because, moreover, the electrical conductivity, the magnetizability, the permanence of magnetism, hysteresis and other properties are dependent upon chemical composition, and as these vary in a manner parallel to hardness, propositions have not been wanting to grade the hardness of iron by its electric, its thermoelectric or its magnetic behavior. v. Waltenhofen, v. Kerpely, Barus and others (*L 196, 197*, pp. 37, *198*).

347. Experience has also taught us that strong materials are usually hard, and hence it has become a habit to speak of hard or soft metals according to results of resistance-tests.

348. It is plain that these conditions commonly existing must add to the difficulties of accurately defining hardness; but it will be necessary to make allowance for such habits, as they can hardly be changed at present. To this the circumstance must be added that a great many propositions for methods of determining hardness, based on appropriate modification of the popular definition first given, have been made, and hence it will be impossible to discuss them individually. I shall rather content myself to give a review of the various methods, and to discuss only those main considerations which may be of interest to one or other of my readers.

The majority of proposed methods for determining hardness may be grouped under the following classification:

I. Hardness is determined by penetration.

A. The penetrating point retaining its original position on the material to be tested. Penetration Method.

B. The penetrating point moves relatively to the surface to be tested. Scoring, Scratching.

II. Hardness is deduced from the resistance properties of the material.

The following sub-classes may be formed under Class I *A*:

1. Impression. A punch is forced into the material by steady pressure, and then determining either:
   a. The penetration due to identical pressure, or
   b. The pressure required to produce identical penetration.
2. Percussion. A punch is forced into the material by impact, and then measuring either:
   a. The penetration under identical impact, or
   b. The impact producing identical penetration.

Under Class I *B* the following sub-classes may be formed:

1. Relative hardness is determined by means of series of standards of different hardness.
2. A scoring or scratching body is forced against the test-piece and:
   a. The pressure necessary to produce a definite abrasion of the material under unit of time or of distance travelled is measured.
   b. The abrasion produced by a scoring substance under definite pressure in the unit of time or of distance travelled is measured.
   c. The pressure is measured which just suffices to produce a scratch of definite width on the test-piece, or
   d. The width of scratch produced by the harder material under a definite pressure is measured on the test-piece.

349. Punches of hardened steel are generally used in Class I*A* for penetration-test, different shapes being used by different investigators. The shape of punch, the hardness, condition of surface, method of penetration, etc., affect the test, and identical results can only be obtained with two apparatus and the same material, or by identical methods, when the predominant parts of machines and the manipulations during test are in all cases precisely identical. But as punches undergo wear, and as it is practically difficult to produce punches of uniformly identical hardness, it becomes necessary in all of these methods to maintain a series of standards which must be subjected to repeated tests between individual hardness-tests, to assure the permanence of the condition of the punches. These punches of course have such shapes that they can always be exactly reproduced by grinding. Attention must then be paid mainly to satisfactory and entirely uniform hardening. The most usual shapes of punches are shown in Fig. 239 (*L 189, 192, 199-209*).

With shape *a*, the length of impression is measured; with *b*, the diameter; with *c* and c_a, when using the spherical end

(Auerbach), the pressure required to produce initial rupture in case of brittle materials, or a permanent impression in tough materials, is measured. Rudeloff, independently of Foeppl (who first published the method), used crossed cylinders at the Charllottenburg Testing Laboratory, instead of the spherical surfaces used by Auerbach, Fig. 239, *ca*. Previous to this, I personally used crossed knife-edges, or cylinders of small radii, for the purpose of comparing them. When using shape *d*, the direct penetration is measured, and perhaps the volume of displaced material, which is used as a factor of hardness (U. S. Ordnance Dept.). Calvert and Johnson determined a pressure which caused the punch *d* of definite dimensions to penetrate the material in ½ hour to a depth of ⅛ in. Keep used a punch *e*, the lower surface of which had 100 small pyramids, on which a 25-lb. weight was dropped from a height of 3 ft. (or 75 ft.-lbs. impact = 288 kg cm). This punch was placed upon the test-piece in such manner, that each successive blow produced impressions of increasing numbers of pyramids, and hence lesser penetration until finally the latter was just visible.

350. Percussion-tests (Class I A_1, *348*) which are no doubt the simplest practically, must be protected from the foregoing sources of errors, and the fact must be borne in mind that the effect of striking and resisting masses of the apparatus must bear identical ratios to each other, and that, taken strictly, the ratio of mass of test-pieces to that of apparatus must be uniform unless the latter are very great. Comparable results can only be obtained by similar methods and different apparatus of like shape when all of these precautions are carefully observed. The masses supporting these apparatus must also be considered if they do not in themselves very greatly exceed those of the acting bodies; they should be appropriately secured.

351. In Class I *B*, the scoring-test, the results are in

all cases absolutely dependent upon the special conditions under which the individual devices operate. The scoring-tools act quite differently on soft bodies cutting like lead and on hard brittle substances. This is particularly noticeable in the grinding methods for determining hardness (Hauenschild, Bauschinger, Smith and others); in these methods there is not a single tool but an infinite number, of most manifold shape, in use. Soft lead is ground with greater difficulty than hard steel under certain circumstances (*L 218*).

The scoring (cutting) action of the tool depends very largely upon its shape, hardness, position, speed of motion and other external conditions. Absolute concurrence of devices and methods must also be secured for apparatus of this class if coincident results are to be obtained at different places.

352. All of the methods thus far discussed have one circumstance in common, that they cannot in themselves furnish measures of hardness, because they apply more or less to the determination of superficial hardness; it always depends, within the individual methods, rather upon the simple comparison of resistance offered by different bodies to a certain method of application of force, and the results of different methods are therefore not directly comparable. It may in fact happen that the sequence of hardness of a series of bodies may be found to be very different when determined by different methods, and may in fact be contradictory. Several of these tests are, however, very convenient, and as soon as they can be made to produce identical values for the same material permanently, it may be a matter of indifference for our purposes whether the values found may be considered, as values of the property of hardness, of scientific accuracy or not. If only the practical result of obtaining a new but reliable standard of comparison for different materials be achieved by the method, and if the result be suitable as

a standard of technological utility of the material for specific uses, it should be considered legitimate. The method would be more suitable, in the degree to which it arranges the materials according to hardness, in conformity with the preconceived notions based on results of experience, which have become our second nature, but which cannot be expressed in figures. Mohs' scale furnishes a sequence of hardness of material, which answers this requirement and has been generally adopted; hence any method for determining hardness must at least not conflict with it. But as absolute value of hardness cannot be expressed* in figures, it depends upon developing the method in such manner that differences in degrees of hardness intermediate to Mohs' scale may be accurately determined.

353. All previous methods were shown to attempt the determination of superficial hardness, and in recognition of this fact attempts were occasionally made to determine hardness of mass. The properties of resistance of materials were generally used as a basis from which the hardness was to be deduced (Class II). Reiser (*L 204*, p. 6), referring to Ledebur, defines hardness as:

> "That resistance of a body which it offers to penetration by another solid—drilling, sawing, filing—or opposes to permanent deformation by crushing or tension.†

* Auerbach claims this for his method based on the definitions of Herz (*L 202*), but the method as proposed by him has slight applicability for our practical purposes. The Rudeloff-Foeppl method will perhaps be more serviceable; the necessary test-piece is at least easily prepared, and permits numerous repetitions of the test with the same test-piece.

† Ledebur says in "Stahl u. Eisen," 1894, p. 479: "The term 'hardness' may be understood to apply to the resistance of a body to 'shaving' (or drilling) ('paring, planing'—Transl.) as well as to brittleness, evidenced by the material when its resistance is called into play in any manner, and therefore undergoes deformation. The latter explanation of hardness is the opposite of pliant."

I have spaced several words, to emphasize the comprehensiveness of this statement and of the difficulty of obtaining a clear understanding

fluous, but the results of resistance-tests would be directly applicable to state the tensile hardness, crushing hardness, bending hardness, etc., with the advantage of utilizing all results of earlier tests in which the E-limit generally corresponds to our S_{Y} directly. But of what advantage would this be in defining properties of materials?

356. There are, however, still other facts to be considered in practical tests of materials. All these methods presuppose homogeneous material. In fact very few materials are really homogeneous, especially among the metals. Let us stick to cast iron! Cast iron, it is well known, consists of a cellular structure of a harder alloy of iron, carbon, and other elements, and of a filling of softer mass of iron with uncombined carbon, which resembles a pit in the cells. Hence if cast iron is subjected to crushing-stress between platens, it is self-evident that the resistance of the harder cellular structure is called into play in a very different manner from that of the softer filling material which, so to say, acts as a packing for the skeleton. Hence all methods of determining hardness, using punches, determine each in its peculiar manner, the mean hardness (which of course is not the case in all results of resistance-tests) of the body composed of cellular structure and filling. All methods determining hardness by means of cutting or pointed tools determine, according to the location of the accidental point of application, the hardness of the structure, or that of the filler, provided the tool does not penetrate the material deeply. Should the latter be the case, the previous effect would result.

357. All circumstances thus far mentioned, and the further consideration that it must be desirable to extend the knowledge of properties of materials by methods as greatly independent of each other as is possible, have caused me to revert to the scoring method when designing an apparatus

for determining hardness for the Charlottenburg Laboratory (*L 188*). I developed Turner's method (*L 203*) of scoring, by providing a diamond *D* with a conical point of about 90° apex, and a slide-rest *S* for the test-piece in Fig. 240, which is moved slowly. The diamond *D* is carried at one end of lever *W*, and can be weighted gradually as desired by moving the poise-weight *L*. Turner made the tests by loading the diamond, producing a decided scratch. While decreasing the load intermittently, successive scratches were drawn side by side, until they became invisible to the naked eye, and then again successively increasing the load until the scratches again became visible. He used the mean load in grammes which caused the scratches to appear and disappear as the measure of hardness. But as it is practically difficult to determine this instant definitely, because skill and sharpness of vision of the observer, favorable illumination, etc., have effect on results, I modified the method by determining the load in grammes on the diamond which produced a scratch of definite width $10\mu = 0.01$ mm (0.00039 in.), or simplifying the method by taking the value of width of line in μ, produced by a definite load on the diamond.

a. The first standard of value is less objectionable theoretically because the widths of lines are not so much affected by the imperfections of the diamond. It is actually very difficult to maintain perfect shape of the diamond points, as they are produced by cleavage and grinding the sharp edges with diamond dust; perfectly ground points would be very expensive.* A diamond point shows roughness and lumps under the microscope, as shown exaggeratedly in Fig. 241, *a*, and the width of line *b* therefore need not always be proportional to

* Grinding would not, moreover, produce absolute uniformity of different diamonds, because they vary in hardness, and because the hardness of one diamond is different in different directions. Iridium-covered steel points have failed.

penetration t. If uniform width of scratch be assumed as a standard of value, the edges will always be in contact with the same points of the cutting surface, the grooves will always have identical section. I must also call attention to the fact that ridges parallel to the scratch are formed in some materials, as shown exaggeratedly in Fig. 241, *b*, and which occasionally make it very difficult, if not impossible, to determine the true width of scratch. If it is not possible by using different illumination under the microscope to obtain a correct knowledge of the error committed, the results of test would have to be considered as approximate, which show too low a hardness. Like materials will always show like phenomena, and will therefore be similarly classified.

It would be too tedious and wearisome to determine the load necessary to produce a certain penetration accurately by actual trial. Hence the approximate load necessary to produce a certain width of scratch is selected, and groups of five parallel scratches are made under varying loads, until the desired width of scratch is certainly contained in one of these groups. Then the different average widths of scratches from each group, and the loads producing them, are plotted on a diagram, as ordinates and abscissæ; from these curves the average line is drawn which gives the load which would have produced the line having width of 10μ. The widths of lines must of course be carefully measured under the microscope by micrometer.

b. The result will be reached more rapidly and easily if the reciprocal value of the width of scratch produced by a definite load be used as a standard of value of hardness; this is moreover quite sufficient for practical purposes when it is a question of rapidly comparing several pieces of a well-known material. In this case 10 to 15 lines are drawn under a load assumed as a unit (10 to 20 gr), and the average width of line is then determined. If the test is always to be made in this

manner, the method and apparatus may be materially simplified.

c. The method of determining hardness according to my propositions of scratching has the advantage, besides its simplicity, it appears to me, that it frequently serves as a means of determining the homogeneity of structure of materials. In cast iron, e.g., the diamond does not penetrate the hard structure as much as its softer filling, and the difference in width of lines is a measure of difference of hardness of these two component parts. There are moreover bodies with cellular structure, the hard parts of which are so brittle that they break off under the diamond, especially when they are at the same time porous, as in that case the diamond point, so to say, drops into the interstices, and then breaks the walls when the piece is moved along (pumice-stone). For such material the scoring method with points cannot secure a standard of hardness. The test would have to be made with a cutting edge, which does not penetrate the material.

d. The hardness of pulverulent material is most readily determined by pressing them into cork; then scratching other bodies of different hardness by them.

e. The hardness of microscopical surfaces can also be determined by Behrens' method (*L 195*), piercing them by hard needles.

f. I do not wish to conceal the fact, however, that great differences of opinion exist in reference to the scoring method for determining hardness (*L 147–149; 188–195*).

In order to remove all doubt about my meaning, I propose to call the hardness determined by the scoring method, the **scoring-hardness**, and designate it by H_s. Hence I shall in future always speak of the scoring-hardness of materials when degrees of hardness determined by my apparatus are referred to.

358. A series of metals showed the following scoring-hardnesses:

Table 27. **Scoring-hardness of Materials as compared with Mohs' Scale.**

Material.	Composition.	Scoring-hardness.	Mohs.
Shellac	—	15.0—17.8	—
Lead	Pb	16.8	1.5
Tin	Sn	23.4—28.2	2—3
Alloy	$CuSn_5$; 97 : 903	36.4	2—3
"	$CuSn_4$; 119 : 881	37.8	2—3
Copper	Cu	34.3—39.8	3
Zinc	Zn	42.6	—
Alloy	$CuSn_3$; 152 : 848	30.0 and 44.6*	2—3
"	$CuSn_2$; 212 : 788	21.8 and 48.7*	2—3
Brass	—	44.7—52.8	—
Nickel	Ni	55.7	—
Alloy	CuSn; 350 : 650	62.5*	3—4
"	$Cu_{25}Sn$; 932 : 68	67.5	3
Soft steel	—	70.8—76.5	—
Alloy	$Cu_{15}Sn$; 890 : 110	78.0	3
"	$Cu_{20}Sn$; 915 : 85	81.6	3—4
"	$Cu_{10}Sn$; 843 : 157	82.5	3—4
"	Cu_2Sn; 482 : 518	83.0	4
"	Cu_5Sn; 729 : 271	100.0	4—5
"	Cu_4Sn; 683 : 317	102.0	4—5
"	Cu_3Sn; 618 : 382	110.0	4—5
Glass	—	135.5	5—5.5
Hard steel	—	137.5—141.0	6—6.5

* Containing hard and soft spots.

The results of tests given in this table may be used for a comparison of the standards of the scoring hardness and the Mohs' Scale, by drawing the diagram Fig. 242.

359. Bodies, the hardness of which is to be determined, do not always have such shape that they can be conveniently placed in the apparatus. The Charlottenburg Laboratory had the problem of comparing the hardness of chilled calendering rolls in use in different works. This could of course only be done in a circuitous manner. I had a series of cold chisels of identical shape as in Fig. 243 made and tempered to different degrees. I determined the hardness of the chisels by the previous method, by scoring. Besides this I secured a set of samples of chilled iron like that used in the rolls. Mutual scoring de-

termined their relative hardness. The rolls were then scored by the same pieces, and they could be classified according to hardness by comparison with the samples. Besides this it was attempted to cut the surfaces of rolls by these chisels, using very light blows. Thus it was determined which of the chisels of different hardness would still produce marks without dulling their edges, and which numbers were dulled. It was thus possible to compare the different rolls according to hardness. This is of course but a crude method, but it can be used for practical work.

l. Toughness and Brittleness.

360. It has thus far been impossible to find a perfectly satisfactory definition for toughness and brittleness, the same as is the case with hardness. Material is commonly called tough when it can undergo great deformation under great resistance; it is said to be brittle when slight deformations produce rupture. Toughness and brittleness are by no means irreconcilable, as it may seem at first glance. Pitch, as has been previously stated, is tough under slow deformation, and brittle under impact. Several values have been proposed as measures of toughness and of brittleness.

361. A number of investigators propose the use of the difference between yield-point (generally called elastic limit by them) and maximum stress, as a measure of toughness [Reuleaux, Reiser (*L 204*) etc.]. Hence toughness would be greater as the yield-point and maximum stress of a material under tensile and crushing stress were further apart. Several values of toughness would thus be obtained, depending upon derivation from tension- or crushing-test. There is indeed good reason for this proposition, but the idea should then be logically extended to all other kinds of stress (bending, shearing, torsion, thrust, etc.); thus a complete series of values of toughness of

a material, which need not by any means be similar to each other, might be obtained.

362. Other investigators have proposed the elongation or the permanent set alone, as a measure of ductility [Hartig, Fischer (*L 10*[illegible]) and others]. They also recognize different toughnesses for tension, crushing, etc.

363. A further proposition, by myself, relates to the use of the contraction as a measure of toughness (*L 205*). This proposition is, however, identical with the previous, as contraction is a function of the factor of elongation at the stricture, in materials of density $= 1$. For, as previously stated in (*36*),

$$c\% = 100\,(1 - a_1/a),$$

and according to supposition that $d = \frac{s}{r} = 1$.

$$V = V_1, \text{ or } al_g = a_1 l_{g_1}, \text{ i.e.}$$

$$a_1/a = l_{g_1},$$

or substituted in above:

$$c\% = 100\,(1 - l_g/l_{g_1}), \text{ i.e. } 1 - c\%(\tfrac{1}{100}) = l_g/l_{g_1};$$

and as in (*33*)

$$e\% = (l_{g_1}/l_g - 1)\,100,$$

or the elongation at stricture:

$$e\%_g = \frac{100}{1 - c\%/100} - 100 = \frac{100}{100 - c\%} - 1.$$

Therefore if the elongation is a practically sufficient measure of toughness, contraction must also answer equally well. In this case it would be a measure of total toughness, which the material can possibly develop up to the instant of rupture, while the elongation is always but a part of this amount, as the cross-sections beyond the stric-

ture become inert after its commencement (*314*, Fig. 220). If $e\%$ and $c\%$ are measures of toughness, $e\%$ is the more preferable, because it is a measure of homogeneity as well. By comparing the proportional elongation (to maximum stress) with the final elongation after rupture, the ratio of development of total toughness of the material could be determined, if of any practical value.

364. Reiser proposes to use the difference between yield-point and maximum stress, as well as the ductility for judging the degree of toughness. A comparison of both standards will give curves 1 for iron and 2 for zinc in Fig. 244, from which it would appear that iron is tougher than zinc when measured by $S_M - S_Y$, while zinc is tougher than iron when compared on second basis because $e_2\% > e_1\%$.

365. The ratio between S_M and S_Y might be used instead of $S_M - S_Y$ as a standard of value, which for the same materials and identical conditions, such as previous mechanical work, cold-rolling, hammering, drawing, heating, quenching, etc., will produce results, similarly to the relation between S_P and S_M, which may be considered nearly constant, hence characteristic of the kind and condition of material. I have found this to be invariably confirmed when tabulating very great numbers of results of tests of our most important materials of construction, and have therefore since several years used the ratio $\frac{S_Y}{S_M}$ to indicate the degree of mechanical work to which material had been subjected. This ratio $\frac{S_Y}{S_M}$ for annealed low steel is equal to 55–75%, while in cold-drawn wire it rises to above 95%. This experience caused me to temporarily use the ratio $\frac{S_Y}{S_M}$ as a measure of toughness.

366. If Reiser's proposition be followed, then **toughness of the material,** by using $\frac{S_M}{S_Y}$ conjointly with e_1, would be

$$T_u = \frac{S_M}{S_Y} . e_1,$$

or up to rupture:

$$T_u = \frac{S_M}{S_Y} \cdot \frac{e\%}{100},$$

which would harmonize still better with practical experience. This value of T_u can be most readily obtained from results of tests.

As the values of $e\%$ in equations for T_u are dependent upon shape of test-piece, or upon the ratio $n = \frac{l_e}{\sqrt{a}}$ (*146*), this is also true of T_u. Hence the index n must be used with $e\%$ and T_u as before to obtain clearness. Hence it should read

$$T_{un} = \frac{S_M}{S_Y} \cdot \frac{e_n\%}{100} \quad . \quad . \quad . \quad . \quad . \quad . \quad 31$$

367. In Table 28 I have classified the values of toughness obtained by the different methods proposed. Columns *a–d* contain the values of toughness of different metals and alloys determined by the methods above described. The last columns give classification of materials according to toughness, arranged under the two heads as given in columns *e* and *f*. These columns, but especially Fig. 245, show that classifications according to $T_u = e\%$ and $T_{un} = \frac{S_M}{S_Y} \cdot \frac{e_n\%}{100}$ agree pretty well, and that they also conform satisfactorily with practical knowledge of toughness of materials.

Fig. 245 gives a classification of metals according to values of T_{un} and of $e_n\%$.

able 28.—Classification of Metals according to Toughness and Ductility according to Different Standards.

Material.	S_Y at.	S_M at.	$\frac{S_Y}{S_M}$	Standards of Toughness. $e_n\%$ *a*	$S_M - S_Y$ at. *b*	$\frac{S_M}{S_Y}$ *c*	$\frac{S}{S}\cdot\frac{e_n\%}{100}$ *d*	Classification according to Standards. *a*	*b*	*c*	*d*	Standards of Plasticity. $\frac{T_n}{S_Y}\cdot 10^3$ *e*	$\frac{Z}{aT}$ *f*	Classification according to Plasticity. *e*	*f*
H. Fischer. Annealed wire.															
) Magnesium.....	136	1410	0.10	2.0	1274	9.7	0.20	1	6	15	3	1.5	(0.1)	9	(2)
) Steel...........	6070	8160	0.74	2.5	2090	1.3	0.03	2	11	1	1	0.005	0.002	1	1
) Platina.........	607	2230	0.27	5.8	1623	3.7	0.21	3	8	9	4	0.4	0.6	3	3
) Lead	62	108	0.57	8.7	46	1.7	0.15	4	1	2	2	24.8	5.5	15	10
) Aluminium.....	374	1380	0.27	9.2	1006	3.7	0.34	5	4	10	6	0.9	1.6	6	7
) Iron............	1750	3040	0.58	14.0	1690	1.7	0.24	6	9	3	5	0.1	0.6	2	4
) Gold.........	114	1110	0.09	17.6	996	10.0	1.96	7	3	16	15	15.4	15.4	14	13
) Zinc............	293	1370	0.21	19.3	1070	4.7	0.91	8	5	12	9	3.1	11.0	11	12
) Nickel..........	1420	4850	0.29	20.0	3430	3.4	0.68	9	16	8	8	0.5	1.4	5	6
) German silver..	1850	4090	0.37	23.9	3140	2.7	0.64	10	15	5	7	0.4	0.8	4	5
) Copper	469	2470	0.19	31.0	2001	5.3	1.64	11	10	13	13	3.5	8.3	12	11
) Tombac	1060	3440	0.31	32.8	2380	3.2	1.05	12	13	7	10	1.0	3.1	7	8
) Silver..........	331	1750	0.19	37.9	1419	5.3	2.00	13	7	14	16	6.0	22.9	13	14
) Brass..........	902	3600	0.25	41.2	2698	4.0	1.65	14	14	11	14	1.8	3.8	10	9
) Tin	40	102	0.39	45.9	62	2.5	1.15	15	2	4	11	28.8	1147.5	16	15
) Phosphorbronze	1270	3400	0.37	55.3	2130	2.7	1.50	16	12	6	12	1.2	—	8	—
Charlottenburg. Averages.															
) Wrought iron:															
Original......	2280	3600	0.64	27.9	1320	1.58	0.45	5	2	4	6	0.20			
Annealed	2090	3330	0.63	28.2	1240	1.58	0.44					0.21			
Quenched ...	3160	4860	0.65	13.5	1700	1.54	0.21	1	5	3	2	0.07			
) Thomas iron:															
Original......	2980	4120	0.75	28.0	1140	1.38	0.30	6	1	1	5	0.13			
Annealed....	2470	3810	0.65	29.6	1340	1.55	0.46					0.19			
Quenched . .	3750	6070	0.62	14.7	2320	1.62	0.24	4	8	8	4	0.06			
) Martin steel:															
Original	2170	3500	0.62	32.7	1330	1.62	0.53	8	4	6	8	0.25			
Annealed....	1760	3170	0.56	37.4	1590	1.80	0.67					0.38			
Quenched ...	3740	5960	0.63	14.1	2220	1.89	0.22	3	7	5	3	0.06			
) Martin steel:															
Original.. ...	2030	3450	0.59	32.6	1420	1.70	0.55	7	3	7	7	0.27			
Annealed ...	1860	3190	0.58	33.8	1330	1.71	0.58					0.31			
Quenched....	3930	5890	0.67	13.8	1960	1.50	0.21	2	6	2	1	0.05			
From Students' Investigations.															
) Low steel 5 bars from	2600	4620	0.54	22.6	1990	1.85	0.41		*			0.15			
to	2770	5020	0.58	29.8	2310	1.73	0.53					0.20			
) Low steel 7 bars from	2890	4820	0.59	26.2	1819	1.69	0.43		*			0.14			
to	3110	5100	0.62	29.0	1990	1.61	0.49					0.17			
) Bronze wire, 3 bars, annealed from	513	1979	0.26	23.0	1401	3.95	0.87		*			1.45			
to	685	(2750)	0.31	32.5	1650	3.23	1.13					1.88			
) Bronze wire, 3 bars, repeatedly ruptured from	2500	2656	0.93	(3.4)	67	1.08	0.04		*			0.02			
to	2766	2952	0.98	9.0	218	1.02	0.10					0.06			

* The values in Nos. 21-24 and 29 do not belong together; they are limiting values taken from e test series. The material in series 21 was not all of the same kind. The wires examined ere mostly tested without annealing.

Table 28.—*Continued.*

Material.	S_Y	S_M	$\frac{S_Y}{S_M}$	Standards of Toughness. $e_n\%$	$S_M - S_Y$	$\frac{S_M}{S_Y}$	$\frac{S_M}{S_Y} \cdot \frac{e_n\%}{100}$	Classification according to Standards.				Standards of Plasticity. $\frac{T_n}{S_Y} \cdot 10^3$	$\frac{Z}{aT}$	Classification according to Plasticity.	
	at.	at.			at.										
				a	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*e*	*f*	*e*	*f*
25) Copper wire:															
2 tests	1120	2420	0.46	30.8	1300	2.17	0.67					0.60			
Annealed....	700	2460	0.28	31.8	1760	3.57	1.12					1.60			
26) Brass wire......	1610	4850	0.33	31.3	3240	3.03	0.95					0.59			
2 tests...	1580	4770	0.33	28.0	3190	3.03	0.85					0.54			
27) Nickel wire ...	3700	4860	0.76	6.3	1160	1.32	0.08					0.02			
2 tests........	3270	4380	0.75	4.2	1110	1.33	0.06					0.02			
28) Nickeline wire.	1920	4520	0.42	28.0	2600	2.38	0.67					0.35			
2 tests........	1990	4490	0.44	26.3	2410	2.27	0.60					0.20			
29) German-silver wire, 3 tests from	2170	5020	0.41	20.2	2670	2.44	0.48					0.21			
to	2350	5270	0.47	24.0	3070	2.13	0.55					0.25			
30) Silver wire, 3 tests from	360	1650	0.22	17.0	1180	4.55	0.61					1.30			
to	470	1650	0.28	34.0	1290	3.45	1.55					4.30			
The same repeatedly ruptured.	1620	1650	0.97	2.3	30	1.03	0.02					0.01			
31) Gold wire	0	730	0.00	13.3	730	∞	∞					∞			
32) Platinum wire..	1020	2150	0.48	6.5	1130	2.08	0.14					0.14			

In order to give a still better comparison of values of $\frac{S_M}{S_Y}$ and $\frac{e_n\%}{100}$ as affecting T_n, I have plotted the values given in Table 28 in Fig. 246, in which the initial numbers of material correspond with those in the table. Points for identical material are united by similar lines, and points for iron are also identified by circles. So as to emphasize the influence of quenching in water on iron, and in values of T_n, the values for quenched iron are marked by parentheses in Fig. 246. The differences relate almost entirely to $e_n\%$, while $\frac{S_Y}{S_M}$ remains constant, although values of S_M and S_Y reported in Table 28 change

according to laws. Comparing the values of silver, No. 30, with those of bronze, Nos. 23 and 24, the great influence of mechanical work* on the ratio $\frac{S_Y}{S_M}$, as well as on $e_n\%$ and hence on T_n, will be noted; the reduction of toughness is very markedly shown.

If it be remembered that Fig. 246 represents the entire field upon which all possible values of T_n must fall, i.e., an inclined plane passing through the origin, it will be seen that all possible values for any kind of material when in a definite condition must fall within a very small space on this plane; all values of T_n found from results of tests would necessarily be grouped about this point, and the C. of G. of this group would be the characteristic value of T_n for this particular kind of material when in a definite condition, as for instance the bracketed group for quenched iron.

368. Whenever in future it will become necessary to compare toughness of materials, the standard of value

$$T_n = \frac{S_M}{S_Y} \cdot \frac{e_n\%}{100}$$

shall be used, and as it can never relate to anything but a comparison of properties of materials, this value shall always be based on tension-tests. It should, however, always be remembered that such comparison, as was the case in scoring hardness, is only a matter of practical agreement, and is in no manner based on a scientific standard of value. Bodies in which values of T_n are very small will as a rule be brittle and have small capacity for resisting impact.

369. Although a hasty glance shows great differences between tough and brittle materials, closer ex-

* The previous elongation during the first tension-test may be considered as such, just as well as cold-drawing.

amination will show numerous transitions, thus justifying the intention of representing toughness and brittleness by the same expression, or of ignoring any difference. We have already learned that pitch is a tough and brittle material. Material which we habitually consider highly brittle, such as glass, may be made very tough by the application of heat. Zinc becomes tougher and more ductile while being heated to 338° F. (170° C.); but a very slight increase of temperature will make it absolutely friable.

Other brittle materials may be so modified by high pressure that, when in this condition, they may be deformed precisely like tough and ductile materials, without producing any cracks or fissures. Kick (*L 100*) could compress and bend materials such as rock salt, when under universal pressure (compression), far beyond the amount which would have been possible in their ordinary condition. Thus he formed relief and lettering by dies on marble, which is a hard and brittle material.

m. Plasticity.

370. Soft, inelastic materials which are at the same time tough possess the property of plasticity to a high degree; i.e., the more a body is soft, inelastic and tough, the more readily can it be subjected to great permanent deformations (changes of shape), drawn into wire, rolled, minted, pressed, or kneaded, without causing rupture.

As stated when discussing hardness (*k, 240*), this property generally rises or falls with the elastic limit. As softness is but a lower degree of hardness (*5*), the standard of value of plasticity shall be determined from the position of elastic limit and of the toughness.

The degree of plasticity will therefore be expressed by:

$$F = \frac{T_n}{S_Y} \cdot 1000, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 32$$

the factor 1000 being added to give more convenient numbers. The values of plasticity thus obtained are given in cols. *e* and *f*, Table 28. The next to last column contains the classification of metals according to values of F.

371. Fischer (*L 106*) had previously proposed another standard for plasticity, and I am bound to explain why I have not joined him. It is due to reasons of practicability alone, for the classification of metals according to Fischer's scale is almost the same (third from last and last col.) as shown by last column.

Fischer determines plasticity in a very circuitous, practically inconvenient, if not an inapplicable manner. He writes:

$$B = \frac{Z}{\alpha T},$$

in which $Z =$ toughness of material, $Z = e\%$; $\alpha =$ the "degree of elasticity"; and $T =$ the "modulus of rupture," our S_Y or yield-point.

The degree of elasticity α is determined from the ratio of factor of resilience a_e to the total resilience a, hence $\alpha = \frac{a_e}{a}$. a_e signifies the total elastic resilience developed by the material up to instant of rupture, both referred to 1 gram of the material.

This ratio can, however, be determined only by a tedious practical test and a consequent complex calculation. As stated in (*41*) when discussing elastic and permanent deformations, it is possible to determine the elastic and permanent elongation of bars independently, by repeated straining. From the values thus obtained the curve of elastic elongation for each stress may be plotted as in curve $\overline{OP2N}$, Fig. 247, in which the elastic elongation $\overline{E_M - E'} = \overline{Oe}$ of the previous stress S_M is plotted as the abscissa for each release of stress, as at $\overline{12}$. If the line $\overline{ON}$ be thus constructed, the hatched surface a_e will be a measure of elastic resilience, which may be compared with hatched surface a of total resilience. It will be seen that this is a very

laborious method which serves no better object than that attained by the equation $F = \frac{T_n}{S_Y} \cdot 10^2$. But this value may be readily deduced from the results of tests, which must be noted in every tension-test as a matter of course, and which do not necessitate further waste of time and labor.

I have previously indicated and am bound to again clearly enunciate the fact that values of hardness, toughness and plasticity have not thus far played as important a part in machine design and testing of materials proper as seemed likely judging by the great trouble taken by technologists about this matter. A difference must here be made between that which is practically valuable and the strict requirements of science. We can only become efficient by absorbing the knowledge which science teaches us, and instead of becoming slaves to it learn how to make it practically useful. Therefore I again wish to point out at the close of this discussion that the values of hardness H, toughness T_n, plasticity F, here given should only be considered as comparative numbers which are purely conventional, and applied to properties of materials which cannot, in themselves, be clearly defined, because it is quite impossible to isolate these properties from each other and study them separately, as a chemist might do in separating each element from a substance and then studying one at a time. We may be well satisfied if our values agree with our practical experience in general, and gross contradictions are not apparent, for it is rarely necessary that materials used in technological processes must be compared in an exhaustive manner as to each and every one of their properties. The problem is usually to determine whether a certain material complies with certain requirements, or to establish a standard of value,—an evaluation of its practical utility,—which is to be discussed in a later section.

B. Technological Tests.

372. Bending and forging tests, which as a group are called technological tests, are made additionally to the resistance-tests thus far discussed, to determine the value and utility of materials Their object is to determine the greater or lesser degree of fragility of material under different temperatures, or to which degree it is malleable when cold or hot, i.e., forgeable.

a. Bending-tests.

373. Bending-tests are made with bar-shaped test-pieces 8" to 12" (200 to 300 mm) length, which are bent either in a special bending-machine, or by hammer on an anvil. The radius of curvature of the neutral axis, Fig. 248, or the angle of deflection *w*, Fig. 259, at the instant of incipient rupture are used as standards of value. The question of a proper method of procedure for obtaining uniform and unobjectionable results has been repeatedly discussed by the so-called "Conferences," and also in other technical circles, but has thus far been but slightly elucidated, because several methods have already been introduced practically, and it is contrary to habit to change a customary method. The bending-test, however, only gives comparative results in figures when made by special apparatus, because it is always more or less dependent upon the skill of the smith when made by hammer. Therefore the "Conferences for Unification of Methods of Testing" adopted the fundamental principle that bending-tests should invariably be made by machine. No agreement about the requirements for the machine could, however, be reached, and hence the old methods still obtain. Hence I shall rapidly describe those devices which are now in use, without advocating any one in particular.

374. The most common test is the hammer bending-test. This is readily understood. Hammer and anvil are found everywhere; hence the test can be readily made. It was an ancient test in smithies, and the smiths possessed great skill in judging the results of tests.

The bar *P* in Figs. 250 and 251 is placed across the edge of the anvil *A*, held down by the sledge *B*, and is then gradually bent by light blows of the hand-hammer *C*. Then the bar is held vertically above the anvil by the tongs *Z*, Fig. 251, and closed down until cracks appear at *a*, or until the sides touch.

375. If the tests be made under a press or a steam-hammer, it is customary to first bend the bar as above, and then placing

it endwise under the hammer or press and closing it down; or it is first bent by the press, being placed on the support *A*, Fig. 252, and forced down by the rider *B* placed at the centre. This second method, which is very generally used, especially in steel-works, caused the introduction of a machine for bending tests, by means of which many hundred tests are made daily. In the Steel-works of Scotland a press with reciprocating stepped plunger *B*, Fig. 253, is used. The first bend is produced in a separate press, and the further deflection is then produced gradually as shown, until the ends are closed down (*L 48*, 1886, p. 434).

376. Mohr and Federhaff build a bending-machine on the principle shown in Fig. 254. The test-piece is held between the cheek-pieces *B* and *A* and then bent about the nose of *A* rounded to radius *r* by the sliding pusher *S*, which carries a roller at the front edge.

377. To avoid friction of bearings as much as possible, and to produce curvature about an edge of uniform diameter, the arrangement shown in Fig. 255 has been used. While the plunger *B* descends, producing curvature about its rounded edge *r*, the bearing-rollers *R* advance to position R_1, thus closing the bar at a uniform rate.

378. Bauschinger constructed the apparatus Fig. 256 (*L 2*), in which the curvature followed a definite curvature *r* from the very beginning. The piece is held between cheeks *A* and *B*, and the roller *R*, carried by a lever, forces the test-piece around the edge *r* of block *A*.

379. The question which principles of method of test embodied in the devices described are to be preferred cannot be answered briefly. It depends principally upon the point whether the simple question is to be decided, "whether a material will stand a certain amount of bending without rupture, or will fail under it, or whether the flexibility of the material up to that point is to be determined." In the first

case, the usual one in practice, the material is merely bent to the desired degree, and inspection will then readily determine whether the requirements have been met or otherwise. In the other case, that of scientific tests, the amount of bending which produces initial fracture is to be determined.

In the first case it concerns the manufacturer to know that he does not suffer by the method of test, and that the apparatus does not affect the material injuriously. The apparatus now in use will only injure the results of tests by secondary strains; the receiver therefore can hardly suffer because of the method of test. The method and apparatus must, however, permit making many tests readily.

380. These methods may be classified according to their principles:

a) those in which bars are bent about a pin, and

b) those in which bars are bent free.

In case *a* the pin may be:

1. of uniform diameter for all thicknesses of test-pieces;

2. the diameter varies according to fixed rules;

3. bending occurs in a constrained manner from the beginning;

4. the bar laps the pin without constraint.

In bending about a pin, the minimum radius of curvature of the neutral axis is determined by the diameter of pin and the thickness of material; when bending free, it is most readily determined by a plug gauge M, Fig. 257, measuring the internal curvature, and the thickness of material a, or still better by an external gauge L and the thickness a, Fig. 258.

381. The extension of the extreme fibre is characteristic for initial fractures. The extension of this fibre for the length $l = 1$ of the neutral fibre, Fig. 259, and the radius of curvature ρ and thickness a is found from

$$l_1 : l = \rho + \frac{a}{2} : \rho \text{ or } l_1 = \frac{\rho + \frac{a}{2}}{\rho}, \text{ also } e = \frac{\rho + \frac{a}{2}}{\rho} - 1 = \frac{a}{2\rho}.$$

The degree of stress is therefore dependent upon thickness of material and radius of curvature, and hence the ratio of these two values is a proper standard of value of the bending capacity of materials.

Under customary notation, as in Fig. 260, we shall have:

$D =$	0	0.5	1.0	1.5	2.0	2.5	3.0a
$\rho =$	0.5	0.75	1.0	1.25	1.5	1.75	2.0a
ϵ	1.00	0.67	0.50	0.40	0.33	0.28	0.25

It will be seen that the angle of bending B_a (commonly used as the standard of value in practice) is not a proper standard of value for degree of stress, which is defined only by ratio of thickness to radius of curvature.

382. $100\epsilon_1$ may also be used as a standard of value, as was proposed by Tetmajer (*L 3*). If curvature be assumed as carried to a semicircle, and the surfaces of ends in contact, ρ will $= \frac{a}{2}$, and $\epsilon_{.\,max.} = 100 \frac{a}{2\frac{a}{2}} = 100$, but when curvature $= 0$ or $\rho = \infty$, then:

$$\epsilon_{1\ min.} = 100 \frac{a}{2\infty} = 0.$$

The standard of value proposed by Tetmajer, hereafter called bending-factor,

$$B_f = 50\frac{a}{\rho}, \quad \ldots \ldots \quad 33$$

varies between 0 and 100 (see table in (*381*)).

383. The radius of curvature may also be determined indirectly, by marking divisions on the tension side of test-piece previous to test, as indicated in Fig. 261, and then measuring

elongation of the divisions after rupture, say between 1_1 and 5_1. If $1 - 5$ was $= l$, then $1_1 - 5_1$ has become $= 1_1 - 5_1$; hence:

$$e_1 = \frac{l_1 - l}{l}, \text{ and as } \rho = 50\frac{a}{e_1}, \rho = \frac{50al}{l_1 - l}.$$

The first method of measuring curvature seems practically simpler. The second is actually not more accurate than the first, whenever the curvature is not truly circular.

It must be borne in mind that the deviation of B_f, above stated, does not agree accurately with occurrences. To show the degree of variation from suppositions, and at the same time to give an indication of actual occurrences taking place during bending carried well beyond the elastic limit, I have represented by Fig. 262 a piece of rubber of square section which was bent until the ends touched. The strip had been previously provided with divisions, as shown by the parallel dotted lines in Fig. 262. All dimensions have been referred to the length of side as a unit, for simplicity's sake.

The left-hand figure shows a section at the point of greatest curvature, drawn to rough measurements. The section has had its height reduced from 1.00 to about 0.80, and its width on the tension side (line A) to 0.79, but on the crushed side (line B) increased to 1.50. The upper or tension side C is concave, the low crushing side, D, convex. Closer examination of the gradual deformation of the latter surface, during test, will show this surface at point marked D in Fig. b is pinched, so that ultimately the original surface is doubly superposed from B to D, forming the hatched meniscus lying between lines $F\ B\ D$, Fig. a; the actual section of bar between lines $C\ A\ E\ B\ F$ is hatched in the opposite direction. If the points where the sections retained their original dimensions most nearly be determined by compass-measurements, they will be found on line E, Fig. b, approximately, while that line on the sides of the strips which does not suffer extension during bending will be found at about G. There is such a

discrepancy between these lines even with crude measurements that the existence of this relation must be admitted. From this circumstance it will be seen that that part of the surface taking the shape of a meniscus actually also takes part in the distribution of stress, and that the occurrences during a bending-test carried to this extreme point are much more complicated than is generally assumed. The displacement of the free (neutral) layer of fibres actually takes place during a much earlier period of the test; but this is not the place to pursue this subject any further. The conditions of extension of individual parts of the bar should, however, be discussed briefly. Extensions are $= 0$ in line G. These and shortening on lines C and B according to rough measurements between dividing lines a and e are written on the respective lines; the changes of length e and $-e$ are noted in parentheses; the ratios $\frac{-e}{+e}$ are bracketed. These measurements demonstrate actual displacement of neutral layer in proportion to degree of curvature. Furthermore, the slight curvatures of the dividing lines on the sides indicate that the sections of a strongly curved bar do no longer remain plane, as assumed in the bending theory. Practically noteworthy is the pinching of the surface at D, because the opinion is sometimes expressed that a rupture took place at that point, but which is actually very rarely the case.

The insufficiency of derivation of B_f is proven by the figures given in Fig. 262, and is moreover logically deducible; for while by deduction of elongation for $\rho = \frac{a}{2}$ for $+e = 100\%$, i.e. $l = e_1 l$, and for crushing $-e = 100\%$, i.e. $l = 0$, the bulging of section B, Fig. 262, would have to be very great, but such is never the case.

The greatest elongation in the previously described test of rubber was found to be $+e\% = 82$ and $-e\% = 48\%$, and similar relation will also be found for soft metals, such as low

steel (Flusseisen) (*L 105*, p. 36). Elongation of low steel is rarely found to exceed 35% in tension; but measured near the point of stricture it will be found much greater (*36* and *363*). The maximum elongation of bending-test probably greatly exceeds that found by tension-test; it cannot, however, reach 100% (*137*, § 52).

384. Although we found that the angle of curvature B_a is not measure of the true stress of material, it is of certain value when judging materials, especially when the bar was bent around a pin from the very beginning. For the greater the angle of curvature, the greater will be the length l of bar subjected to stress; the greater will be the probability that this length contains one point which may be the cause of rupture. It may be said that this agrees with the purposes of test, for the object is to produce transverse fracture, and the producer has no reason to complain about increased severity of test when under proper selection of B_f 180° of curvature be prescribed.

385. The bending-test is made either with flat, nicked or punched bars. These strips when of soft material may be cut by the shears or punch, but in these cases must be trimmed on the edges by machine tools or the file. The edges at which the bars are to be bent should be rounded to a radius of about $\frac{1}{4}a$, because the presence of sheared edges or square corners is often cause of cracks, which are not due to defective material, but to preparation.

386. In order to give proper consideration to the law of similarity, which also applies in the case of bending-tests, provision has been made at the Charlottenburg Laboratory that test-pieces have the following dimensions proportional to thickness t:

$$t = a; \text{ width } b = 3t; \text{ total length } L = 18t.$$

The test is made on a press as in Fig 252, using a length $l = 15t$; the apparatus is arranged to comply with this condition readily. The radius of the curved end of punch is $r = t$.

387. If nicked pieces are to be tested, it will be necessary that the producer and the purchaser agree upon a method of nicking. It is easiest to nick the bars with a cold-chisel, cutting to a depth of .04 or .08 in. [or still better of $(0.1\text{–}0.2)t$], Fig. 263. The material is not so easily injured, and uniformity is more readily preserved by planing the grove. The bar is then bent with the nick located on the tension side, at the section of maximum stress.

388. In case of the perforation bending-test, the strip is perforated at the centre, Fig. 264, and it is then bent so that the diameter of hole coincides with section of maximum stress. The test is less severe when the hole is drilled than when it has been punched. Diameter of hole d, width of strip b and thickness t should always bear the same ratio as nearly as possible, about $d = 2t$ and $b = 5t$. If punching is prescribed, the method of producing the hole should be specified, for it is not immaterial whether the strips be punched or the strip be cut from the sheet after punching.

389. In case of very soft materials, such as copper, it is customary to cut a thread on the bar before making the bending-test. This is of course a more severe test.

390. Bending-tests are usually made on the material when in different conditions, in order to obtain a most comprehensive opinion about its properties. Cold-bending tests are made either at ordinary temperatures or after artificial cooling. Recently temperatures of $-40°$ F. (40° C.) have been used for testing iron and steel. Melting ice is used for producing 32° F. (0° C.); $-4°$ F. ($-20°$ C.) is obtained by mixtures of crushed ice and rock salt or snow; still lower temperatures are obtained by solidified carbonic oxide (*296*). These tests were to prove whether the materials investigated became more brittle and fragile by cold. It is customary to

call bending-tests made under atmospheric temperatures simply cold-bending tests.

391. So-called hot-bending tests are made while the material is at a blue or red heat. Both temperatures are important for iron, because it may become much more fragile at these, under certain conditions, than when cold or bright red. Iron is said to be at a blue heat if it shows no red color upon withdrawal from the fire, but a freshly filed surface takes a blue color, and retains this color for some time; the test must then be rapidly made. If the temperature was too high, the color will disappear; if too low, it will not appear at all. Strips are most conveniently heated in a lead-bath or a heating-furnace. This test shall be briefly called the blue-heat test.

The red-heat test is made as soon as the strip has been heated so that it shows a red color plainly when shaded. By experience these temperatures are readily judged.

392. It is important to know the properties of some materials in an annealed or quenched (hardened) condition. To anneal pieces reliably, they are heated uniformly to the maximum temperature under which the material is not injured, and then buried in dry cinders from a smith's fire. Thus they cool gradually during several hours. Quench-tests are made on strips plunged suddenly, when at the most effective temperature, into a bucket of water at temperatures of from 59° to 86° F. (15°–30° C.), and hence rapidly cooled; it must not be forgotten to move the bars about while in the water, and that a sufficient quantity of water be used to avoid material increase of temperature of the latter. The bars are then tested as already described, when cold. The circumstances under which pieces are quenched play an important part in some materials.

b. Wire Tests.

393. In course of time a special method has been developed for testing wire. The postal department and mine authorities in Germany were the instigators. There are definite specifications for telegraph and hoisting-rope wire. Besides the tension-tests usually made by manufacturers of hoisting-rope on each wire, bending- and tension-tests are also made.

394. Bending-tests are made by a special apparatus, based on the following principle: The wire is clamped between jaws of a vise, Fig. 265, having edges *r* of definite curvature. Wire *D* passes loosely through a guide *F* fastened to a lever *H*, which turns about centre *M*. The wire can then be steadily and slowly bent from position 1 to 2 and 3 consecutively and back again. The bend 1–2–1 or 1–3–1 is counted as a full bend, and the number of bends borne by the wire before rupture is noted.

As a rule the curvature at *r* and length of lever from point *M* of rotation to *F* are alone prescribed. In this case, as we have seen, the stress produced in wires of different thicknesses cannot be the same. As different standards are used, different numbers of bends should be prescribed for different thicknesses. In order to comply accurately with the law of similarity the radius *r* and length *MF* should be taken proportional to thickness of wire. In this case equal numbers of bends could be prescribed for like material of different diameters.

395. A further technological test commonly prescribed for telegraph-wire is that it should be wound upon itself (and when very soft to be again unwound). This fulfils the law of similarity directly.

396. Carding- and spring wire must be especially tested for uniformity of elastic properties. This is

commonly done during the bending-test, by clamping the wire in the moderately rounded jaws of vise BB, Fig. 266, then bending it down sharply into the position 2, and letting it return to position 3 by its own resilience. The ratio between radius of curvature of vise-jaws and half-diameter of wire will be the measure of bending-factor B_f, and the angle a the measure of resilience of the wire. If thicker wires are to be tested, cheeks of different curvature r must be inserted.

397. It is frequently specified that telegraph-wire be capable of being twisted a definite number of times about its axis in a given length, as a rule in 6 inches (15 cm), before rupture. One end of the wire is fixed to a spindle, Fig. 267, and a carriage at the other, which permits free motion longitudinally. Occasionally a light weight P is attached to stress the wire. The number of revolutions of the crank up to rupture is counted. The law of similarity also applies in this case, and hence comparative results can only be obtained, not when a definite length of wire is used, but when a definite ratio $\frac{l}{d}$ between free length and diameter is prescribed. In this case alone an equal number of twists may be borne by different thickness of wire of like material. With equal length the number of twists prescribed should decrease for increase of diameter.

c. Forging-tests.

398. Forging- or hammer-tests are made on material either when hot or when cold—at blue or red heat when made hot. The particular method must be specially adapted to suit the object to be tested. Forging- and hammer-tests are therefore so manifold that but a few can be described here.

399. That most generally made is called the spreading-test. In this test flat bars are spread by fuller, length-

wise and crosswise; the increase of breadth b_1 and of length l_1 and decrease of thickness a_1 are measured, Fig. 268. The test is continued until cracks appear in the edges. The necessary temperature, in certain cases, must be maintained by reheating during test.

The law of similarity also applies in these tests, and it will be well not to forget it when comparing test-pieces of very different dimensions. I therefore prescribed that the uninjured ends of bending-test strips be used in the Charlottenburg Laboratory, or else other pieces of similar dimensions. When making tests it must be noted that test-lengths $l = 1.5$ to $2b$ be invariably spread or stretched, and that then the shoulders S, Fig. 268, be particularly well developed on the test-piece. The hammered end should have, as nearly as possible, uniform thickness throughout during test. The formula

$$Fl = \frac{b_1}{b} . 100 \text{ or } Str = \frac{l_1}{l} . 100 \quad . \quad . \quad . \quad . \quad 34$$

may be recommended as standards of value for spreading and stretching.

400. The upsetting-test, especially used for rivet-material, and generally at a bright red heat, is made on a plug of length $l = 2d$ (diameters), which is upset until superficial cracks appear. The proportional shortening may be used as a standard of quality as in (*238*):

$$e = - e_1 . 100.$$

401. The perforation- or drifting-test is generally made at bright red heat by means of the drift, succeeded by pins of larger diameter until cracks appear at the edges, the strip being reheated as required, Fig. 269.

The standard of quality is obtained by ratio of dimensions of hole before and after test. by expanding:

$$Exp. = \frac{d_1}{d} . 100. \quad . \quad . \quad . \quad . \quad . \quad . \quad 35$$

The law of similarity should of course be borne in mind when comparative tests are desired; as in the perforation bending-test (*388*), $d = 2t$ and $b = 5t$ should be used. Sometimes the distance c, Fig. 269, is also specified.

402. It is customary to point bars to be used for horseshoe nails or in nail manufacture to determine the behavior of the material; they must draw out to a fine point without checks or splitting.

403. Welding-tests are also made, by splitting a bar and then again welding it together. The perfection of weld is determined by cold-bending test, making the bend at the weld. Sometimes tension-tests are made of the welded pieces.

d. Various Tests.

404. Shape-iron and other similar material is frequently tested in the finished shape, and these tests are often prescribed in specifications.

Angle-iron for shipbuilding is bent cold into shapes as shown in Fig. 270, *a–d*. The flanges are cut and then flattened out as in *a* and *b*, or rolled up as in *c* and *d*. The latter are especially apt to develop defective spots and cracks, due to defective ingots and piles, which remained unwelded during rolling.

405. Plate is tested according to the purposes for which it is to be used, whether to be drawn down to a thin edge at corners, or flanged as in boilers. Drifting-tests are sometimes prescribed for sheet copper. The French Government requires this. According to Baclé (*L 104*, II, p. 209) it prescribes that a bowl of radius ρ and depth f, Fig. 271, be formed of a disk of radius R and thickness a, and requires

$$\text{for } t > 0.25 \text{ in.} : f = 4 \text{ in.};$$
$$\text{for } t > 0.12 \text{ in.} : f = 4.75 \text{ in.};$$
$$\text{for } t < 0.12 \text{ in.} : f = 6 \text{ in.}$$

The dimensions should, however, be proportionate to thickness of sheet in these requirements, to comply with the law of similarity; for thickness of sheets up to 0.4 in. the above dimensions may be stated as $\rho = 20 \times t$; $f = 22t$.

If possible, the test should be made by machine, without hammers, which may be done as shown in Fig. 272. A plate, $R = 32a$, is pushed through the perforated die having rounded edges of $r = 4a$ and diameter $= 44a$, by a plunger of radius $\rho_1 = 18a$, until cracks appear, or until it fits the plunger. The depth of depression at instant of initial cracks in terms of a serves as a standard of value. If these ratios be used for plates varying from $\frac{1}{8}$ to $\frac{1}{2}$ in. thickness and the dimensions be changed for each increase of thickness of 0.078 in. (2 mm), 5 dies and plungers of rough cast iron will suffice.

If very thin sheet metal $a < 0.078$ is to be tested similarly, it might be well to use plungers with hemispherical ends of $\rho_1 = 18a$, and disks of $R = 32a$, and to force them into a thick plate of lead, instead of through a die.

If greater or less stress is to be developed than that assumed under proportions given by the French specifications, the ratios a/ρ, etc., are to be relatively increased or decreased. Similar tests of iron plate have been made in Sweden in conformity with Fig. 271 and an impact machine (*230*).

406. The French State Railway, according to Baclé (*L 104*, II), prescribes forming a cylindrical flange with flat rim, as in Fig. 273, for testing sheet copper of less than $\frac{1}{2}$ in. thickness. But for this test as well it would be advisable to prescribe definite ratios of dimensions, as without them there would be no measure of actual stress. The following dimensions, in multiples of a, should be determined: R, R_1, r and l.

Hand-work should be avoided in this test as much as possible; this may become possible by driving a conical plunger through the ring into an annular former, Fig. 274. The ratio $r_1/R_1 . 100$ at the instant of initial rupture may be used as the

standard of comparison. The conical cast-iron plunger should be made as smooth as possible, and to be covered with graphite before test. I should temporarily recommend the following dimensions:

$$R_0 = 18a,\ L_0 = 50a,\ R_2 = 22a,\ R = 32a,\ R_1 = 10a.$$

Different dies only are necessary for the apparatus, as the plunger can be used for all cases.

Thin sheets $a > \frac{1}{8}$ in. might be tested on a lead block, as explained in (*405*), in which case the a plunger with conical end, as in Fig. 274, would be required.

407. Flanging is a common test for tubes and connections of malleable metals, as in Fig. 275. In this case definite ratios of dimensions should also be prescribed, although it is not a very simple matter, as thickness and diameter may both vary.

Considerable success in omitting hand-work was achieved in the Charlottenburg Laboratory; in addition to the flanging-test, the method of expanding as shown by Fig. 276, in which a smooth cone of definite dimensions, covered with graphite, is driven into the pipes or tubes; it is advisable to use a cone having the ratio of $R_0 : L_0 = 1 : 2.5$, Fig. 274. The standard of comparison may in this case again be the ratio of expanding $\frac{r_1}{r} . 100$. It must, however, be remembered that the ratio $\frac{a}{r}$ affects the deformation.

408. Beside the flanging- and expanding-test, upsetting- and crushing-tests are also made at Charlottenburg on sections of pipe having a length equal to external diameter, for the purpose of developing the character of the pipe material. Fig. 277 shows characteristic phenomena, previously described in (*255*), occurring in tubing of soft material of different thicknesses.

It is also customary to flatten pipes sidewise and then to double them over as in Fig. 278, and then to note cracks. In

welded or soldered tubes the joint should be placed in the section of maximum bending-stress.

409. The apparatus shown by Fig. 279* is used for making comparative tests of elasticity and hardness of steel balls for ball bearings, in which the balls, following each other at proper intervals, roll down a trough set at a definite angle, and then drop on a flat hardened plate. From this plate they jump, according to their varying elasticity and hardness, to different heights, and must pass over an interposed obstruction in order to be considered suitable for a definite purpose. The unsuitable are thus simply sorted out.

e. Hydraulic Tests.

410. Vessels, pipes, etc., as units, or parts thereof specially prepared, are tested by internal pressure. The objects of such tests are to determine either their stanchness under a prescribed internal liquid or gas pressure, their freedom from deformation, or the resistance of the material in the shape of the vessel. In the latter case it is an object to determine to what extent the resistance found from a standard test-bar is utilized in the construction. It would be necessary to study the theory of resistance of vessels in order to obtain a complete knowledge of the occurrences of a pressure-test. This would, however, be beyond the scope of a book on testing materials. While referring to other works on resistance of material, and especially that of Bach (*L 137*), for this theory, I shall treat solely of cases which are important in testing materials; these are tests of vessels (generally tubes) which are called "thin," and for which the stress of the material is readily determined by the formula

$$S = p\frac{d}{2t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 36$$

*Patented in Germany (DRP 89231) by E. Peitz, Berlin.

if S be the stress produced by hydraulic pressure p in a vessel of diameter d and thickness t. The longitudinal stress produced by the pressure, because generally very small, is neglected. It is, however, self-evident to determine in each case in which manner this simple formula is applicable.

411. The test is usually made by water-pressure, because this produces the least possible danger from flying pieces at the instant of rupture, because then the elasticity of the material alone is the acting force. It is necessary to take extraordinary precautions for safety, because of the energy existing in compressed gases when making rupture-tests by compressed gases, or when there is even a possibility of rupture. Hence the hydraulic test only shall be discussed.

Pressure is generated by small hand-pumps, unless it is excessive, and it is measured by gauges, usually spring-gauges. If high-pressure systems are available, as is the case in the Charlottenburg Laboratory, the testing is very simple and convenient. The material to be tested is coupled to the high-pressure pipes carrying a pressure of 420 at. by a copper pipe about $\frac{1}{8}$ in. inside and 0.4 in. outside diameter and 50 to 65 ft. long, which is very flexible and can stand pressures up to 5000 at. A valve-chamber is coupled between the test-piece and pressure system, which at the same time controls connections with one or several gauges, or branches to other places. If several systems are to be connected, the coupling used with greatest success at Charlottenburg and shown in Fig. 280, having a double-ended steel cone and which has been found absolutely tight under pressures of 5000 at., is commended.

412. If spring-gauges be carefully used and carefully guarded against shock, they show very slight changes and may be used up to very high pressures. The Charlottenburg Laboratory has gauges reading up to 2000 at. These gauges are frequently compared with each other, and with others kept for this purpose alone, thus making any pos-

sible changes readily noticeable; besides this several gauges are used simultaneously in important tests. To protect gauges on testing-machines and in hydraulic tests against shock, check-valves as shown by Fig. 281 are used. A disk perforated by a very small hole closes the opening of the gauge-duct by a fine spring. The pressure-water raises the disk and then passes through the grooves in its edge with very slight hindrance to the gauge, while the small hole alone permits its return.

413. The apparatus shown in Fig. 282 is used at Charlottenburg to produce pressures from 400 at. to 700 at.; it is a steel casting which is fitted to a testing-machine of 220,000 lbs. (100,000 kg) capacity; it is provided with a packing of a leather U collar, which has been found satisfactory at pressures of 900 at.; it has an admission-valve by means of which it can be refilled from the mains without removal from the machine. The pressure in the main forces the piston back after release of load by the testing-machine. The pressure may also be calculated from the load indicated by the testing-machine and the diameter of plunger (+ packing friction), and is a very good check on the gauge-readings. The apparatus has also been used in connection with the standard gauges for the purpose of comparison and calibration of testing-machines.

For producing very high pressures up to 10 000 at. a press like Fig. 282, with a ring shrunken on the outside, like those on guns, is used at the Charlottenburg Laboratory in the 100 000-kg machine.

414. The Charlottenburg Laboratory has frequently had occasion to make hydraulic pressure-tests in a testing-machine without use of gauges or a press, especially when an approximate determination of very high bursting-pressures, of rifled and smooth gun-barrels, was sufficient. The test was made as shown by Fig. 283. Two loosely fitting bolts were inserted in each end of the barrels, and short pieces of black rubber hose, passed over the conical ends of these bolts, served as packing. One of these bolts was secured by a

cap screwed over the end of the barrel, and the other was forced into the heavy oil in the barrel by the testing-machine, which measured the load. In this manner it was possible to determine the bursting-pressures of very thick-walled vessels, such as guns.

The rubber sleeves could be made tight, although with some difficulty, even in rifled barrels. Perhaps this method will be still more satisfactory by using the gelatine solution described below. Similar tests have also been made with carefully turned hard rubber or metal sleeves, but the use of pieces of rubber hose is so easy and simple that it is as a rule preferred. In our laboratory they answered for more than 3000 at.

415. For testing pieces of pipe without flanges or similar bodies, in which it is difficult to attach a tight seal, a method similar to the previous has been used at Charlottenburg. As shown in Fig. 284 the two pipe ends were packed with leather cups, which, being scraped thin at the edges, adhere closely even to rough walls. If the walls of the pipes were, however, too rough, they were smoothed off by means of resin-wax putty, which should not be wanting in any testing laboratory. This putty may be readily made by melting proper amounts of the two substances together. To produce a still better joint, the cups may be flowed on the inner surface with glue which has been somewhat macerated by chromate of potash to make it insoluble in water. This glue-jelly acts like a rubber cushion and presses the edges of the cups tightly against the walls of the tubes. The cups are backed by loosely fitting plungers, which take the pressure of the testing-machine as in the case of the rifle-barrels (*414*), when tests may be made without a gauge. If the pressure is to be determined by a gauge, a sealed tube must be connected to the vessel. This is done most readily by means of one of the plungers and a cup, made as shown at *a* and *b*, Fig. 285. The cup is either provided with a smaller cup at the centre, through which the pointed end of the plunger is forced, its

edges acting as a sleeve and packing it, or a special small cup as at *b* is sewed to the bottom of the larger cup, sealing the seam with pitch or wax. It is still better to fill the cup with glue as shown in Fig. 285, *b*. For heavy pressures the tube must be prevented from being forced out by the reaction.

416. The devices shown in Figs. 282 to 284 of course answer only in case the tube material does not suffer large deformations, for if these occur the cupped leather will finally be blown out between the plunger and the surface of the tube. When material spreading may be expected to occur, provision must be made for it. This is done at Charlottenburg either by fitting a sleeve over the tube ends, or winding them by wire under tension as in Fig. 286, *a* and *b*. Under these conditions the cupped leather packing has answered under the highest pressures; it is used even for the smallest pipe; for very large diameters above 39 in. (1 m) U-shaped cupped collars are used.

417. If the use of the testing-machine to resist pressures is inconvenient for any reason, bolted frames, as shown in Figs. 287 and 288, may be used. When the bolt passes through the centre, the pressure on the end surfaces of the packing may be materially reduced by providing a very limited amount of play between the surface of tube and the surrounding chamber, and packing the same by a U collar.

418. To avoid the use of end rings or wire wrapping when testing very soft materials the device shown in Fig. 289 may be tried. The packing of the tension-rod is accomplished by a U collar, and that at the ends by an angular ring of soft rubber packed with layers of linen. This ring may perhaps be made of a long piece with tapering ends, so as to be suitably fitted to different diameters of tubes. Its section should be about as shown in Fig. 290, so that the sharp edges turn outwardly, and then fit the inner surfaces neatly upon insertion. To obtain this packing at the inner tube surface satisfactorily initially, it is well to use an elastic split ring, as indicated in Fig.

289, consisting of a bent brass strip, etc. This rubber packing will probably follow the expanding tube. Unfortunately there has not yet been an opportunity to test this device at the Charlottenburg Laboratory; it would certainly simplify tests materially.

419. The devices thus far discussed mainly served the purpose of preventing longitudinal stress, so as to permit the circumferential stress to act as much as possible. It is, however, customary practice in pipe-testing machines to prevent leakage at ends, mainly by causing them (flanges) to simply bear against thick rubber disks on the heads of the machines, with sufficient pressure to make a tight joint under hydraulic pressure. This method is undoubtedly the simplest for making simple and numerous pipe-tests when metal pipes, cast pipes, etc., are to be tested, and is not at all objectionable; but when tile and cement pipes sometimes having irregular ends are to be tested by internal pressure it is questionable, because the pressure of the rubber may introduce indeterminate and sometimes even dangerous stresses in the pipe.

420. If the circumferential as well as longitudinal stresses are to act on the test-piece simultaneously, then the pipes are closed by flange-plates or screwed caps. Where this is impossible, as in sections of metal tubes, the method shown in Fig. 291 was adopted in suitable cases at the Charlottenburg Laboratory. The pipe was sealed by providing several sawcuts in the pipe end, inserting the leather cup as in Fig. 286, and then inserting a slightly conical plug. Thereupon a conical ring is forced over the split end of the pipe so as to close it down on the inner plug. This seal was very satisfactory even for very high pressures.

421. Measurements of deformation generally consist of determination of permanent deformations after test, and are most conveniently made by wrapping a thin steel tape about the outside. For making finer measurements at the Charlottenburg Laboratory I constructed the ap-

paratus whose principle is embodied in Fig. 292. One end of the steel tape *S*, wrapped about test-piece *P*, marked by dotted line, is connected to the rod *L* and is loaded at the other by the weight *G*. A fine string tensioned by the spring *f* is connected to the steel tape, and wrapped about the roller *r* of an indicator. The circumferential changes of the tube may thus be readily indicated on a 10- or 20-fold scale. The pipe must be lightly tapped by a wooden mallet before each reading, so as to eliminate the friction between the tape and the test-piece. The apparatus has worked quite satisfactorily.

422. A definite problem, which may be considered as a test of material, shall therefore be here described; it was the testing of iron flasks for transportation of compressed or liquefied gases.*

Governmental hydraulic tests, which are to be repeated from time to time in some countries, had been prescribed for such vessels. These flasks must not show permanent set after test by specified pressures. Permanent deformation may be determined either by circumferential measurements or by the quantity of water contained before and after test by weighig. Then difference in weight gives the expansion directly.

423. If measurements are to be made during the tests, the danger of rupture must be considered and suitable arrangements provided. This may be done as indicated in Fig. 293; there are several similar devices (*L 48*, 1895, I, p. 553) in use. The flask *F* is connected to a cover *D*, the joint being packed in any manner, as by a rubber ring *R*. Flask and cover are placed in a closed vessel *G* containing water. If pressure from a pump or an accumulator be admitted by pipe *P*, the elastic deformation of the flask will cause the water to rise in tube *M*

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* The complete tests of materials for gas-flasks will be found in the Reports (*L 185*), where bibliographical references will be found.

and indicate the expansion of flask on a multiplied scale depending upon the diameter of the gauge-tube. The indications on *M* after release will show the permanent expansion of flask *F*. It is self evident that the thermal condition of apparatus must remain constant during test. Leaks of *F* will vitiate the test, and it must also be borne in mind that accurate measurements can be obtained only when account is taken of elastic changes due to height of column *M* (change of pressure in external vessel) or when they are eliminated altogether. This is done most readily by allowing the larger mass of displaced water to flow into an enlargement of *M*, and then merely noting the differences, as between pressure 0 or maximum at the small tube *M*. These parts of the tube may then be placed horizontally, thus avoiding material differences of pressure in the external chamber entirely.

As tests of flasks are usually made in great number, it is advisable to arrange the apparatus conveniently for quick work and for flasks of all sizes. I have designed such a device for the Charlottenburg Laboratory. The cover of this device, which is the most essential part, is shown in Fig. 294. It is arranged in such manner that it can be screwed to the flask at the same time with the pressure-pipe connection. The connection carries a loose collar on the coarser thread, which may be forced against the cover by means of a nut and pins (handles). This forces the flask firmly against the rubber packing-ring let into the cover. The whole can then be set into the outer vessel by means of two handles, the rising water-level displacing all air, until the cover finally rests upon the rubber ring in the upper edge of the outer vessel, sealing the latter satisfactorily. The cover merely rests on the outer vessel by its own weight, thus acting as a safety-valve in case of rupture. The whole apparatus is let into a pit, thus avoiding accidents as nearly as possible. The small disk carried by the locking-bolt serves only to hold the loose collar.

III. Standard of Quality for Technological Value of Materials of Construction.

a. In General.

424. The full technological value of a material can only be known after it has been in service in a manner so as to develop all of its valuable properties. The latter rarely happens. As a rule material is generally used in such manner as to develop only some of its properties; occasionally the material is to develop but a single property. The standard of value to be applied to any material as to its quality and utility may therefore be a totally different one, under the conditions just stated, than if it were desired to express the sum of all of its properties. This cannot be done accurately, because a valuation in a complete manner is absolutely impossible. An approximate evaluation of the quality of the material may therefore be obtained from partial tests based on the requirements which it must fulfil in a special case, or generally comply with in common service.

As a matter of course, it is not possible either for the engineer or the merchant to wait until actual use has demonstrated the suitability of the material. It is therefore necessary to derive the strength of a detail of construction from preliminary tests and measurements which have been fully discussed in the chapters on testing. This has always been the practical method, by comparing the results of tests with those of actual experience, thus obtaining a mass of experimental data, which is the subject of study in testing materials.

The foregoing will demonstrate that it is impossible, at this time, to discuss the different points of view for judging the value of materials exhaustively.

At this place, as was the case in the discussion of testing materials, it is only possible to consider the general points of view applicable to the majority of materials; special methods of test, as well as evaluation of definite materials, can only be taken up when discussing the properties of such materials.

b. Development of Standard of Value.

425. In materials of construction, especially metals, the resisting properties are most commonly considered as a standard of value. The methods of doing it are manifold. The figures obtained from tension-tests are those most frequently used as standards of utility of many materials. Heretofore the maximum stress S_M (tenacity) has been used with elongation $e\%$. Reduction of area, contraction $c\%$, was also largely used in Germany, although with opposition of the manufacturers. This standard has latterly again gone more into disuse in Germany, while elsewhere it still seems to be adhered to.

Considère, in France, has particularly advocated the use of contraction $c\%$. He considers it of great importance (*L 105*, Chapt. II and III), using it to determine c (*36*). He asserts that this is the standard of serviceability in constructions (*363*, *L 205*), and states particularly that c at section of maximum bending-stress should be the standard of value of material, because c is fully developed. (This can of course only be the case (*382*) in materials for which $c < 100$.) Considère attempts to emphasize and elucidate the value of his view by a comparison of S_R of tension-test referred to area of fracture, and the stress of extreme fibre $+ S'$ in bending-tests.

Because he considers the total elongation of test-piece to be composed of the proportional elongation e_e of the whole bar and of the local elongation near fracture e_q (*142*), he proposes to make a comparison of the two, and use it as a standard of value to establish the ratio $\frac{e_e}{e_c}$. Similar propositions were previously

made at different places, and there would be much in favor of it if it were not more difficult to determine e_e than desirable for practical tests of material.

Besides what has been said in (*140*) it is necessary to observe that the so-called proportional elongation can be determined only on very long bars $\left(\frac{l_\varepsilon}{\sqrt{a}} > 11.3\right)$, in which the effect of head may be considered minute. In such bars it would be possible to determine the ratio $\frac{e_e}{e_c}$ after rupture with comparative ease by determining the areas of fractured section and that of a part of the bar at some distance from the fracture. In short bars it would be necessary to determine an approximate value of e_e during test by using e_e at maximum stress S_M, i.e. e_M, or by determining the mean section of bar at maximum stress by actual measurement. The value of e_M might be determined with some accuracy from an autographic diagram.

In every case, however, the value $\frac{e_e}{e_c}$ would be subject to uncertainties; it would depend especially upon measurements of test-bars, as is the case with $c\%$.

426. The three values S_M, $e\%$ and $c\%$ will no doubt remain standards of quality for a long time henceforward, because they can be determined most readily and reliably.

Although, as was emphasized in the discussion of Bauschinger's tests of changes of elastic limit, and of the Woehler repetitive tests (Chap. II, *i*), the determination of S_P would be of incomparably greater value to the constructor than that of S_M, it need not be expected that it will be introduced in practice, because difficulties inherent in testing are too great to be overcome. It would be much easier to consider the value of S_Y, because machines commonly used are constantly being perfected, so that this point may be determined with some certainty. It may be noted that at present much greater value is placed on the determination of the yield-point, and we have seen, **that its actual location, as well as its relation to S_M, are suitable to define properties and conditions of material.** This point will appear in

a more striking manner in the special discussion of properties of materials (*L 110*).

The location of the *P*-limit is, however, already introduced emphatically by some authorities in gun and rifle manufacture as the standard of quality for the material to be used, because the constructor in this branch of technology must make the highest demands in regard to material, as the powder, recently highly perfected, generates exceedingly high pressures in guns, although their lightness and their movability must remain very great. But still the difficulty of determining S^P must there be well known.

c. Specifications.

427. Wherever large quantities of materials of construction are used, it is customary for the purchaser to very carefully specify the qualities of the material to the producer. It is customary to state in the contracts at least the tenacity S_M and elongation $e\%$ which the material is to show, and sometimes the contraction $c\%$ or the *P*-limit and *Y*-point as well. The lower limits of values alone are generally stated. But it also happens that maximum limits are also stated. This is the case in low steel for structures, in which it is customary to exclude the very soft as well as the very hard kinds below 51,200 and above 64,000 lbs. per sq. in., because the former cause permanent set in certain members too readily, and because the hard metal may be dangerous on account of its frequent brittleness. Experience with low steels has taught us that this danger increases with decrease of elongation and high strength. But it is not possible in steel-works to produce at a commercial price steel of any desired properties, and hence it is necessary to insert limiting values in specifications with greatest care and conscientiousness. This is a difficult matter of exceedingly great import. For if the values be stated so as to make the material obtainable, but only with unusual difficulty, the

user will have to reimburse the producer for his extra trouble, labor, and expenses. If the values are technologically inappropriate, the structure will suffer in safety and durability. The economic development of the capabilities dormant in crude materials is incomplete if the material produced does not possess all of the good qualities which a process when commercially correctly managed can develop in or add to it.

The first two points of view are hardly ever overlooked, for their omission invariably acts directly on the pocket. The third is, however, a matter for the economist, who should assist, as far as lies in his power, to perfect the productivity of raw materials by development and improvement of industry.

Specification requirements slightly above the average of quality of materials in common use are apt, as a rule, to act beneficially on the perfection of technological processes, and on the improvement of national capability. But great care must be exercised not to use these particular values as the lower limits in specifications, because this easily produces totally unnecessary difficulties of production. The producer in this case must furnish a better material than contemplated by the lower specification limits, if he does not wish to bear losses due to rejection of material by the purchaser, and the quality must be better by the possible variation ordinarily found in all materials when taking all possible precautions. The average quality of materials will therefore always be a little above that called for by the specifications. In this it is of course presupposed that ample and conscientious care be had to meet specifications.

If the lower limits are made unnecessarily high and above the commonly readily obtainable average of quality, as can be done by a purchaser, who, like the State, because of the mag-

nitude of requirements and for other reasons, occupies a powerful position toward industries, their welfare may suffer by these unnecessary requirements.

The points of view here developed for enunciation of standards of value are of a general character. The presentation of particular values for each material must, however, be deferred to the discussion of properties of materials. Technological improvement and economic conditions have great effect on these values by themselves, and hence they are subject to frequent variations.

d. Standards of Quality.

428. If any material is to be identified in a most comprehensive manner by the results of the tests mentioned, the values given in Table 29 must be determined.

A complete knowledge of properties of a material of construction requires a knowledge of modifications of these properties under the effect of very low and very high temperatures, but it has thus far been avoided to make this matter a subject in specifications, and it need not be expected that this will be done in calculable time. I have therefore neglected these points in the preparation of Table 29.

This table and the foregoing discussions will show, that maximum stress and elongation are the two principal standards of quality for our materials of construction.

e. Factors of Quality.

429. Stress can be determined with certainty only in such materials in which it is possible to measure the original sectional area accurately. In case of ropes, cloth, paper, leather, and many other materials, in which density $d = \frac{W_v}{\text{Sp. G}_v}$ (*21*) is less

Table 29.—Compilation of Standards of Quality.

The standards most commonly used are printed in heavy-faced type.

	Resistance-tests.			Technological Tests.
	Tension.	Crushing.	Bending.	
Resistances	S_P, S_Y $\mathbf{S_M}$ or l_R	S_P, $\mathbf{S_Y}$ or $\mathbf{S_M}$	S_P, $\mathbf{S_Y}$ or $\mathbf{S_M}$	**Bending-test, B_f and B_a.** (Bending-factor and angle.) Cold {quenched, annealed} / Warm {blue heat, bright red} — {normal, nicked, punched}
Deformations	e_P or E or e_f e_n; $\mathbf{e\%_{11.3}}$ $\mathbf{c\%}$	e_P, e_Y e_M	e_P or $\frac{e_P}{l_g}$ e_f or E $\mathbf{e_Y}$ or $\frac{e_Y}{l_g}$ $\mathbf{e_M}$ or $\frac{e_M}{l_g}$	**Reverse bending-test: wire.** Winding-test: wire.
Fracture	Structure	Structure	Structure	**Hammer-tests** (cold and blue heat): spreading-test, stretching-test.
Degree of workability	$\frac{S_Y}{S_M}$	—	—	**Forging-tests:** spreading-, stretching-, drifting-, and welding-tests.
Toughness	$T_{n.11.3} = \frac{S_M}{S_Y} \cdot \frac{e\%_{11.3}}{100}$	—	—	Upsetting- and drifting-test.
Plasticity	$F_{11.3} = T_{n.11.3} \cdot \frac{1000}{S_Y}$	—	—	Internal-pressure tests.
Hardness	By method (*348–359*) (specially recommended: scoring hardness, or Foeppl method).			See foot-note.*

Also: Results of chemical and physical investigations.

* Shearing- and punching-tests are rarely made, in which S_M is usually determined. Impact bending-tests are used for railway material. Impact upsetting tests should receive greater consideration.

than 1, or in which the section is irregular, or in which consecutive sections vary considerably from an average, it is very difficult to determine the value of that section which is actually subjected to stress. A body which is nearly uniform, although not homogeneous in structure, like a strip of a textile fabric, may be conceived of such length as to cause rupture by its own weight, or any desired stress, when supported at one end. The length of the body which would produce rupture is called its rupture-length, and is designated by l_R in Table 29. This length is found from L_M, the load at rupture, and the weight of unit of length W_1; hence it is:

$$l_R = \frac{L_M}{W_1} \text{ in meters, or} \quad . \quad . \quad . \quad . \quad . \quad 37$$

$$l_R = \frac{L_M}{W_1 1000} \text{ in km.} \quad . \quad . \quad . \quad . \quad . \quad . \quad 37a$$

This expression obviates the determination of the section, being replaced by weight, which is almost always determinable. It will be seen that l_R is a constant for each material; it is independent of section, and, large or small, the rupture-length will remain the same. The assumption that the result of test must be independent of shape of section is taken as self-evident.

It is easy to deduce stress from rupture-length, if the Sp. Gr. of the material be known. If this = Sp. Gr., one ccm of the material will weigh $\frac{\text{Sp. Gr.}}{1000}$kg, or one meter = 100 cm of section a:

$$W = a \,.\, 100 \,.\, \frac{\text{Sp. Gr.}}{1000} = a \,.\, \text{Sp. Gr.} \frac{1}{10}, \text{ hence}$$

$$a = \frac{W \,.\, 10}{\text{Sp. Gr.}}; \text{ and as}$$

$$L_R = \frac{L}{W} \text{ and } = S\frac{L}{a}, \text{ then}$$

$$S = \frac{L}{W} \cdot \frac{\text{Sp. Gr.}}{10} = L_R \cdot \frac{\text{Sp. Gr.}}{10} .^* \quad . \quad . \quad . \quad . \quad 38$$

The great value of L_R for our purposes will be seen from the following:

It is common custom among manufacturers to weight materials, i.e., to increase their weight by the addition of cheaper materials. Every trade has whole series of refined terms for this process, and becomes very touchy when such are not employed, but replaced by plain every-day expressions which every one understands. I will be understood when I explain that paper, for instance, used for wrapping butter which the housewife buys contains 45 to 50% ash, because of the extra addition of white clay, instead of a maximum of 2%. The difference is due to dressing. When buying 4 oz. of butter, it is frequently the case that 12 to 18% of paper is paid for at the price of butter. The paper for wrapping loaf sugar frequently contained 60% ash while sugar was dear, and even the twine for tying the loaf was loaded. Leather, rubber, silk, wool, and innumerable other goods often contain large masses of weighting materials (dressing) which are usually very much cheaper than the goods which have been loaded.

430. Weighting is always resorted to for the purpose of increasing the weight beyond its normal standard. If it be assumed that such weighting material does not otherwise affect the strength of material, such as rope, leather, rubber, cloth, or paper strips (as a rule it is also reduced), it becomes clear that the rupture-length is decreased by this weighting because of the increased weight of the unit of length. It will be seen that the rupture-length is a very good means for defining the true value of certain materials.

431. Just as rupture-length takes cognizance of two properties of materials, viz., resistance and unit of weight, it has been attempted to establish values based on the principal results of tests, which, combining the

* S, as will be seen, relates to the solid section (voidless). If S for section of material, say a rope, is desired, then W_v, weight of unit volume, is to be substituted for Sp. Gr.

various properties to a certain degree, furnish standards of utility of the material, and are called quality factors, or factors of utility.

The quality factors most generally used are those named after Woehler and Tetmajer, although their origin antedates these investigators. Woehler's factor is formed by the addition of tenacity S_M and the reduction of area $c\%$ (in metric values); if $S_M =$ 44 kg sq. mm (62 500) and $c\% = 30\%$,

$$\mathfrak{W} = 44 + 30 = 74,$$

$$\left(\text{or } \frac{S_M}{1000} + 30 = \frac{62\,500}{100} + 30 = 92.5, \text{ English measure.}\right)$$

Tetmajer's value is obtained by the product of tenacity and elongation, or the work done up to rupture. If in this case $S_M = 44$ kg sq. mm and $e\% = 21\%$,

$$\mathfrak{T} = 44 \times 21 = 924,$$

$$\left(\text{or } \frac{S_M}{1000} \times 21 = \frac{62\,500}{1000} \times 21 = 1312.5, \text{ English measure.}\right)$$

Both values were frequently used in specifications a short time ago.

f. Importance of Quality Factors.

432. As previously stated, it is customary to insert minimum limits for values of S_M, $e\%$ and $c\%$ in specifications for materials of construction. Representing this by diagram Fig. 295, all possible values of S_M, $e\%$, $c\%$ for the material in question, for instance low steel (Flusseisen), must lie within the quadrants drawn.

By introducing the lower limits by S_{M_l}, $e\%_l$ and $c\%_l$ in specifications it is customary to exclude those qualities which are unsatisfactory for structures, namely the weak and the brittle kinds.

433. If Woehler's value be stipulated instead of these limiting values, the heavy broken line $\mathfrak{W}$ would be the limit of rejection. If this value $\mathfrak{W}$ alone were prescribed, material having very high tenacity and very small contraction, or very low tenacity and very high contraction, might also be furnished under the specifications, which is material certainly quite unsuitable for purposes of construction.

Woehler's factor in itself is therefore not a standard of quality, for it includes entirely unsuitable as well as suitable material. Poor materials can be excluded only by use of minimum limits of S_M and $c\%$ additional to Woehler's factor. The sole advantage derived from the addition of Woehler's factor is, as shown by Fig. 295, the exclusion of material otherwise accepted if the sum of $S_M + c\%$ be made greater than would be found from the lower limits, or

$$\mathfrak{W} > S_{M_l} + c\%_l.$$

434. If Tetmajer's factor be used instead of the limits above discussed, line $\mathfrak{T}$, Fig. 295, materials of low tenacity and small extensibility are excluded, but it must also be explained that this factor measures materials which are certainly not of the same value by the same standard, for the same factor may be obtained by high tenacity and low elongation, or by low tenacity and high elongation. Tetmajer's factor has, however, a certain advantage over that of Woehler's, although the circumstance that material of very great differences in resistance and elongation is not produced is equally advantageous to both factors. But even when using Tetmajer's factor it becomes necessary to state minimum limiting values S_M and $c\%$ if reliably suitable material is desired, and

hence the factor $\mathfrak{T}$ is also rational only when $\mathfrak{T} > S_{M_l} \times e\%_l$ is used. In this manner the slice at the lower part of the diagram will be cut off.

435. In order to give these factors a different character, that of an equable average, specifications have been changed artificially, finally giving one or the other of these factors a certain limited lower variation beyond the limits S_{M_l}, $e\%_l$ and $c\%_l$, provided that either $\mathfrak{W}$ or $\mathfrak{T}$ be met, that is, provided the relative sum or factor was correspondingly greater. The advantage thus apparently favoring steel-works will appear very materially limited if it is considered that it must be balanced against the slice which is cut off, and that the area gained (that indicated by the hatched slices between lines S_{M_l} and S'_{M_l}, $c\%_l$ and $c'\%_l$, or $e\%_l$, $e'\%_l$, (Fig. 295) is very limited; for the steel industry should naturally attempt to introduce uniformity based on conditions which are commercially advantageous.

If it is convenient for any works, because of the raw material and methods available, to produce a material, the tenacity and elongation of which would be plotted at M, Fig. 296, it becomes clear that the bulk of its product will show similar properties. If, therefore, tests were to be made of each melt and results plotted in a diagram, it would be found that values S_M and $e\%$ would be grouped mainly about point M. If these points were considered material and superposed, a mound would be produced the apex of which would lie at M, its ordinates of altitude being a scale of frequency, with which a material of definite S_M and $e\%$ would be accidentally produced, when an effort is made at a given works to produce steel of the qualities represented by M. The slopes of this mound would at first drop very rapidly toward $S_M = 0$ and $e\% = 0$, and then very gradually. This may be represented by drawing contour-lines around the mound through points of equal frequency. The quantity of material falling within the slices S_{M_l} S'_{M_l} and $e\%_l$ $e'\%_l$, and $c\%_l$ $c'\%_l$, Fig. 295, would indeed be very small and

would have to be counterbalanced by the mass of material about the apex between S_{M_l} and $c\%_l$ or $c\%_l$, if the steel-works are to gain the benefit of an equable average. (*L 114.*)

Because of the reasons stated I cannot become very enthusiastic about either of the quality factors thus far introduced. To this must be added the fact **that the quality factor alone cannot be deduced directly by test; the separate factors must moreover be determined, and in order to be able to form a conception of the quality factor, at least one of its factors must be known.** Therefore, why not state both factors at once? And when knowing these, of what use is the quality factor?

The justified average is in my idea only imaginary. Ultimately it is always a question of a definitely fixed limit. If this limit was correctly selected in view of the safety of a structure and economical production of the material, its adoption is perfectly justified. Manufacturers are always prone to the accusation that it is hard and unjust to demand complete fulfilment of specification requirements. For a slight drop of one value, say of S_M, would be counterbalanced by an augmentation of the other, say $c\%$. It is customary to assert that limits of errors of methods of testing do not justify such a strict procedure. From an impartial standpoint it must be admitted that the first objection would be valid if the technical correctness can be demonstrated. In that case the limits selected would, however, have been unsuitable. If there can be no valid objection against these, it is not unjust to adhere to them rigidly, because the second objection is unjustified, for, according to the theory of probabilities, the errors of observation are just as often positive as negative, and results of limiting cases are as likely to be in favor as against the interest of the manufacturer. This is of course only true **when the method of test employed is not subject to large erorrs** of **method,** when it is in itself inadmissible.

IV.

Machines for Testing Materials.

INTRODUCTION.

436. The character of testing-machines has been briefly sketched in Chapter II, and the requirements which they must fulfil have appeared in general in the previous chapters; many peculiarities have already been touched upon. Here, where a more detailed presentation of the most usual designs will be given, it does not answer to merely give a general review of existing machines, but those principles are to be developed which must be considered during their construction, calibration and application.

But as a testing-machine is usually a very complicated tool, which may be arranged for making various kinds of tests, a classification according to definite ideas is very difficult and justice can hardly be done in all directions. I must therefore, in making an attempt to solve this problem, ask the indulgence of my readers. I am of the opinion that descriptions of testing-machines in a handbook on testing materials must be of practical value. For practical use, therefore, the book is to give information for the selection of machines for all requirements; it must indicate which machines are in the market readily obtainable, and which are examples of exhibition-machines, intended for specific purposes, in small number. I have therefore classified machines now in the market on Plates 3 to 20, arranged as nearly as practicable according to

the builders, with statement of proportions to which they are built, in various forms. I have drawn largely upon price-lists when the illustrations appeared sufficient for the above purpose. The addition of constructive sketches and of schematic diagrams of each type, given separately and on the plates, will facilitate elucidation and description.

I shall, as much as possible, describe the machines in groups, in order that similar designs may be found together. Therefore it is not always possible to give a description, complete in itself, of an entire machine, because this would be too extensive as well as tiresome. At the end I shall give a grouping according to makers, in which the missing descriptions *will* be found, with references to sections containing detailed descriptions. For those readers who wish to study individual machines in minute detail I shall add the bibliography known to me.

I shall attempt to exercise a free but benevolent criticism in every particular. I hope that this criticism will be of value to the user as well as to the builder of machines. At the same time I am cognizant of the fact that every criticism is more or less one-sided, and that everybody occupied exclusively with a practical technical subject unwittingly appropriates biassed opinions. I must therefore be content if not every one will consider my remarks as absolutely appropriate; but my attempt shall be purely objective. For this reason I would accept every criticism and all advice with pleasure and if possible make use of them in future editions.

I hope that my experience will enable me to give encouragement toward perfection and progress, and shall therefore occasionally look beyond the things existing.

A. Machine Types.

437. For the grouping and description of machines I desire to give, in connection with the classification

previously given (*L 113*), a schematic review. In this it is not possible to utilize all details of machines; I shall rather confine myself, as a rule, to the arrangements for tension-tests as a basis, because these after all are most generally used, and therefore the most important; it is also most frequently determinative for the constructive development of the machine.

438. In every machine the following essential parts (Chapter II) may be identified:

the loading mechanism,
the weighing mechanism, load indicator, and
the frame.

To this must be added the apparatus for measuring deformations produced. But this part is not necessarily integral with the machine, does not affect its character and can be considered separately.

439. The character of a testing-machine appears to me to depend primarily upon the relative arrangement of its three essential parts. Secondarily the general arrangement, whether horizontal or vertical, is important, and finally the peculiarities of construction, of loading mechanism, of load-indicator and of jaws, holders or grips, must be considered. I have therefore used the arrangement of loading mechanism and load-indicator in the machine-frame as the starting-point for my classification.

440. The type of load-indicator often causes very essential peculiarities of design, which are mostly very apparent externally. I have used this circumstance as the basis of my first grouping, and distinguish between machines in which loads are determined by

Scale (lever-scale with weights or spring-balance) and by

Hydraulic pressure (gauge or hydrostatic balance).

441. These groups are again subdivided, without regard to horizontal or vertical construction, according to the method of arrangement of loading mechanism and load-indicator, and primarily as to whether

loading mechanism is at one end and the load-indicator at the other, or
both are at the same end of the machine.

In the case of vertical machines it is important to note whether one or the other of these devices is placed on the upper or lower part of the machine. This distinction is dropped in case of horizontal machines.

442. The method of transmitting loads from the loading mechanism to the test-piece and from the latter the load-indicator may have an essential influence on the design of the machine, and may produce certain advantages or the contrary. Accordingly I also distinguish as to whether the loading device or the load-indicator are

in direct or indirect connection

with the test-piece, i.e., whether loads are transmitted over the shortest path or whether in a roundabout manner, by avoiding important structural parts, through connecting-rods, cross-heads, etc., etc.

443. I shall give a schematic representation of the various types of machines growing out of these considerations, giving the names of builders using each type. The dates of first construction of the various types as far as I could determine them will also be stated. References to publications whence I obtained my information shall also be given, and the numbers of the paragraphs in which the various types are mentioned or discussed are also added.

444. Before proceeding to further discussion it must be here stated that in order to abbreviate descriptions, I shall indicate load-indicators, regardless of detail of construction, by con-

ventional representations as shown in Figs. 297 and 298. Fig. 297 indicates that the machine belongs to the first type, in which loads are measured by a scale; while Fig. 298 indicates hydraulic measurement of loads. The loading device regardless of detail construction shall be represented by Figs. 299 and 300. Fig. 300 indicates that the machine is considered as arranged for tension-test; *z* indicates the test-piece, and *m* the jaws or grips. Fig. 301 indicates that the test-piece is to be loaded as for crushing. When the test-piece is attached directly to loading device or load-indicator, this will be indicated by Fig. 302; when indirectly, by Fig. 303. Parts of the frame of machine which are considered as rigid will be shown hatched as in Fig. 304; in this the peculiar design of detail is disregarded. These conventional designations, along with those in (*65*) for the several forms of load-indicators, will be used hereafter even when discussing the more detailed schematic representations of special types of machines.

445. Hence the grouping of types of machines may be as follows:

Machines of the First Group: Load-indication by scale.

1st Principal Type: Loading and indicating device at opposite ends.

Load indication direct.

Load device above $\begin{cases} a) \text{ direct, Fig. 305.} \\ b) \text{ indirect, Fig. 306.} \end{cases}$

Load device below $\begin{cases} c) \text{ direct, Fig. 307.} \\ d) \text{ indirect, Fig. 308.} \end{cases}$

Load indication indirect.

e) Loading device above, indirect, Fig. 309.

f) Loading device below, indirect, Fig. 310.

N.B.—In horizontal machines *a* and *c* and *b* and *d* coincide.

Construction (*v.*=vertical; *h.* = horizontal) according to type:

a) Fig. 305:	v. Gollner,	1879.	Sect.	598–601, 452, 479, 490, 492, 493.	Plate,	13.	L *220*.
	v. Grafenstaden,	1868.	"	583–586; 492, 433, 518.	"	8.	L *12*, 1882, p. 8.
	h. Wendler,	1887.	"	539, 543.	"	11.	L *215*.
	h. Werder (50 *t.*),	1852.	"	565.	"	4.	L —
b) Fig. 306:	h. Hoppe,	1894.	"	591–598, 457, 493.	"	10.	L —
c) Fig. 307:	v. Carrington,	1878?	"	537.	"	—	L *102*; 183.
	v. Chamond,	?	"	479.	"	15.	L *102*.
	h. Delaloë,	?	"	516.	"	15.	L *102*, 183; 34, 1888, p. 5.
	v., h. Greenwood and Batley,	1865.	"	619–622.	"	17.	L *48*, 1879, Sept.
	v. Martens,	1884.	"	524, 530; 546; 566–573, 508, 523, 563.	"	5, 11, 13.	L *113*; 115; 162.
	v. Michaelis,	1878?	"	509.	"	—	L *183*, p. 14.
	Michele,	1878?	"	535.	"	—	L *183*, p. 13.
	v. Mohr & Federhaff,	?	"	574–582, 72, 376, 479, 492, 493, 517.	"	6, 7.	L *12*, 1884, p. 141; *27*, 1882, p. 545.
	v. Paris-Lyons (Marié)	?	"	476.	"	15.	L *102*, 183, 245.
	v. Pfaff,	1887.	"	485, 496.	"	13.	L *19*, I, No. 9.
	v., h. Riehlé,	1889.	"	636–639, 460, 526–528.	"	19.	L *51*, 1881, p. 147.
	h. Rudeloff,	1884.	"	546.	"	—	L *115*.
	v. Schopper,	1890.	"	536, 331, 543.	"	11.	L *228*.
	v., h. v. Tarnogroki,	?	"	537, 531.	"	—	L —
	v. Trayvou,	?	"	—	"	15.	L *102*, *183*, *251*.
	v. Wicksteed,	?	"	611–618, 485, 519.	"	16, 17.	L *49*, 1884, p. 180; *243*. *55*, 1886, II, p. 27. *48*, 1886, II, p. 176.
d) Fig. 308:	h. Adamson,	1885.	"	—	"	—	L *52*, 1885, II, p. 84, 250. *48*, 1887, I, p. 564.
	h. Kirkaldy,	1865.	"	619–622.	"	17.	L *121*; 48, 1879, Sept.; 246.
	v. Wicksteed,	?	"	611–618, 485, 519.	"	16, 17.	L (above under *c*)

2d Principal Type: Loading mechanism and load-indicator at the same end of the machine.

g) Loading and indication direct, Fig. 311.

h) Loading indirect and indication direct, Fig. 312.

i) Loading direct and indication indirect, Fig. 313.

k) Loading indirect and indication direct, Fig. 314.

These types are exemplified (horizontal = *h*.; vertical = *v*.) in

g) Fig. 311:	h. Buckton,	?	Sect.	485, 611–618.	Plate	17.	L —
	v. Creusot,	?	"	—	"	15.	L *102*.
	h. Hartig-Reusch,	?	"	542, 483, 539, 540, 543–545.	"	11.	L *215*.
	v. Reid,	(1878?)	"	509*a*.		—	L *47*, 1878.
	h. Werder,	(1852.)	"	483, 489, 495, 497, 564–573, 453, 483.	"	3.	L *239*.
i) Fig. 313:	v. Fairbanks,	1883.	"	529, 486.	"	—	L *45*, 1884, Feb.; *12*, 1884, p. 84; 113.
	v. Olsen,	1880?	"	640–643, 486, 525.	"	20.	L *102*; *113*. 51, 1879, p. 36; 1883, p. 39.
	v. Riehlé,	1889?	"	same as in *c*, Fig. 307.	"	19.	L same as in *c*.
k. Fig. 314:	v. Pohlmeyer,	1879?	"	532, 587–590, 534*a*–*e*, 465, 493, 533.	"	9.	L *229*.

Machines of the Second Group: Load-indication by gauge.

A. Pressure is measured at the Hydraulic Cylinder.

3d Principal Type: Load mechanism and indicator at same end of machine.

l) Loading direct, Fig. 315.
m) Loading indirect, Fig. 316.
n) Loading indirect, Fig. 317.

These types are exemplified by (*h.* = horiz. and *v.* = vert.):

l) Fig. 315: *h.*	Kellogg (Athens),	1887.	Sect. 473, 474.	Plate —		*L* 48, 1887, I, p. 413.
	Stummer,	?	" —	"	—	*L* 23, 1883, p. 198.
m) Fig. 316: *h.*	Greenwood & Batley,	?	" 622	"	17.	*L* —
n) Fig. 317: *h.*	Curioni (Desgoffes, Olivier)	?	" 455	"	15.	*L* 210.
v.	Whitworth	1850.	" 552	"	—	*L* —

B. Load-indication by Separate Chamber.

4th Principal Type: Loading mechanism at one end nd indicator at other.

Pressure chamber actuated negatively.
Pressure chamber actuated positively.

) Load-indication direct. (Pressure-chamber actuated negatively).

Loading mechanism above { *o*) direct, Fig. 318. *p*) indirect, Fig. 319. }
Loading mechanism below { *q*) direct, Fig. 320. *r*) indirect, Fig. 321. }

) Load-indication indirect. (Pressure-chamber actuated positively.)

Loading mechanism above { o_1) direct, Fig. 322. p_1) indirect, Fig. 323. }
Loading mechanism below { q_1) direct, Fig. 324. r_1) indirect, Fig. 325. }

For horizontal machines *o* and *q* and *p* and *r*, as well as o_1 nd q_1 and p_1 and r_1, are identical.

Constructions according to these types are:

q) Fig. 320:	*v.*	Chauvin and Marin-Darbel	1876.	Sect. —		Plate 15.	*L 102*; 183; 241.
o_1) Fig. 321:	*h.*	Emery	1876.	Sect.	623–635, 483, 485, 501, 559	" 18.	*L 214, 219, 242.*
q_1) Fig. 324:	*v.*	Amsler-Laffon,	1887.	"	602–609, 453, 477, 550, 561	" 14.	*L 3.*
	h.	Maillard	1878 ?	"	556, 557	" 15.	*L 102*; *183*; *209*.
	v.	Martens	1884.	"	same as *c*, Fig. 307.	" 5.	*L* same as *c*.
	h.	Thomaset	1878 ?	"	555	" 15.	*L 183*; *240*.
	h.	Unwin (Bailey)	?	"	—	" —	*L* *240*; 47, 1881, p. 41; *52*, 1882, p. 361; *11*, 1882, vol. 146, p. 127.

P r e s s u r e - c h a m b e r a c t u a t e d n e g a t i v e l y.

P r e s s u r e - c h a m b e r a c t u a t e d p o s i t i v e l y.

L o a d i n d i c a t i o n i n d i r e c t.

Driving mechanism above s and s_1 direct, Figs 326 and 327.

Driving mechanism below t and t_1 direct, Figs 328 and 329.

In case of horizontal machines s and t and s_1 and t_1 are identical.

None of these types have been constructed.

[Attention is called to Figs 323 and 326, for, while the functions of parts are the same, the loading mechanism in Fig. 323 acts on the near end of test-piece, while in Fig. 326 it acts on the far end. The same is true about Figs 325 and 329. —G. C. Hg.]

5 t h P r i n c i p a l T y p e: Driving mechanism and load-indicator at same end of machine.

C h a m b e r a c t u a t e d n e g a t i v e l y.

C h a m b e r a c t u a t e d p o s i t i v e l y.

u) Loading mechanism direct, Fig. 330.

v) Loading mechanism indirect, Figs 331 and 332.

Constructions according to types are:

v) Fig. 332: *v.* Amsler-Laffon, ? Sect. 602–609, 453, 477, 550, 561. Plate 14. *L 3.*

446. In machines of the 4th and 5th principal types the pressure-chambers may be actuated negatively (Figs 318–321, 326, 327 and 330) or positively (Figs 322–325, 328, 329, 331 and 332). In the first case increased loading produces

decreased pressure in the chamber, in the latter increased pressure. In the former in types o to r the pressure is applied directly to the diaphragm of the chamber, i.e., to the movable part of the chamber; in the latter case, o_1 to r_1, the pressure is applied indirectly. If it is desirable to arrange the types according to the practically essential distinction of negative or positive loading of the pressure-chamber, the types o_1 to v_1 would have to be added to the 4th and 5th principal types.

It is to be noted that types o and q (o_1 and q_1) and p and r (p_1 and r_1) concide when machines of the 4th principal type are constructed horizontally.

B. Loading Mechanism and Frame of Machine.

a. Hydraulic Loading Mechanism.

447. The loading mechanisms and frames of machines are generally composed of detail rarely differing essentially from ordinary machine construction. It is therefore unnecessary to go into detail. I shall hence confine myself to general remarks.

448. Loads are either applied mechanically or by hydraulic power. The latter is generally the most efficient and convenient; it is much in use. This is by no means intended to decry the forms of mechanical loading devices (compare the following sections and *480*).

449. Power is generated by hand-pumps, which are generally directly connected to the machine, or by power-pumps; the latter especially in case of large machines or when several are to be driven. In large industrial establishments it is common to make a high-pressure system, really used for other purposes, available.

450. When one pump drives several machines in use simultaneously, it is necessary to provide an accumulator in the system, which temporarily absorbs the excess duty of the pump, to be utilized when several machines are operated at the

same time. Capacity of pump, of piping and of the accumulator must not be designed too sparingly, when several machines are to be operated simultaneously or where increased facilities may be contemplated. Water-pressure may at this date be easily raised to 500 at. (7500 lbs. per sq. in.). Most machines are operated at pressures much below this, and 80 to 150 at. will represent the average.

It is of some importance in larger laboratories, in which several machines are to be used, and where the rooms are exposed to frost in winter, whether water or glycerine is to be used in the system; mixtures of water and alcohol have also been recommended. When glycerine, oil or other liquids are to be used, return-pipes must always be provided; in these cases it should never be neglected to provide filters or purifiers in the outlet system. The use of viscous liquids such as glycerine, oil, etc., requires piping of larger dimensions than for water, to avoid frictional losses or slow transmission of liquid; valve openings and passages must also be ample. If proper provision is not made in this regard, this error will become noticeable by heating of the liquid and of the valve-chambers.

When urban water-pressure is available and a high-pressure service planned for the machine, the latter can be operated economically by the city water-pressure when running light. The Charlottenburg Laboratory is thus equipped. Double piping and special valves are of course required, but the saving of high-pressure water is material and the adjoining machines are much less disturbed.

451. When using a hand-pump, its operation is directly adjusted to the requirements of the test in hand. Hand-pumps usually have a large plunger for large delivery and under low pressures, and a small plunger for small delivery under high pressures. When using power pumps regulating-valves controlling the speed of plunger must be provided.

1. Pumps.

452. I shall here mention but a few types of pumps which deviate more or less from usual forms, and such as were especially designed for use with testing-machines.

Simple hand-pumps, designed for the Werder machine, are shown on Pl. 3, Figs 1, 2 and 6, detail numbers 30–37. Lever 31 operates the large and lever 32 the small pump.

The Ehrhardt hand-pump, Pl. 9, Figs. 28 and 29, has telescopic plungers, which can be so connected to the hand-lever by bayonet-lock that either the small plunger alone, or both plungers together are effective.

The hand-pump of the Gollner machine is peculiarly arranged, Pl. 13, Figs. 1–3, 16 and 17. It is placed at the head of the machine; it is arranged for hydraulic as well as for screw power.

453. The Amsler-Laffon hand-pump used on their 75,000-lb. (35,000-kilo) machine is shown in Figs. 1–6, Pl. 14, and in detail in Fig. 333.

The plunger 42, Fig. 333, is forced by the crank 32 and the gearing 38–41 into the cylinder filled with castor oil. The advance is very slow with large ratio. A quick jerky reverse motion of the crank throws a peculiar tripping-wedge in the keyway into gear, thereby coupling a pair of wheels operating the rapid-return motion.

454. The principle employed in this apparatus has been repeatedly used in various forms, as (1878) with the Maillard machine (*L 209*, p. 19, Pl. I, Figs. 15 and 16), in the Desgoffes design. A hollow plunger of about 3.9 in. diam. (10 cm) and 24-in. stroke (60 cm) is driven by hand or belt power and a screw into a special press-cylinder, which then operates the testing-machine.

455. A peculiar design of pump (hydraulic press) is found in the Curioni machine (*L 210*, p. 2, Pl. I, Fig. 2). It is

built according to the designs of Desgoffes and Ollivier, as shown in Fig. 334. The plunger is advanced by the displacement of the liquid in the cylinder 2, produced by winding a flat strap 6, passing through a stuffing-box 7, on a drum 8. Reversing the motion winds the strap on drum 5, and atmospheric pressure returns the plunger. 9 and 10 are gear-wheels driving 8. The vessel 13, with cocks 12 and 14, serves to replenish the cylinder. Is this press really serviceable? It is rarely used. The drawings given in the reference are crude and incomplete; judging by these, the Curioni machine seems to possess other weaknesses.

456. Power pumps for operating testing-machines are made in many forms. Most of them are three-plunger pumps with automatic release, which comes into play upon reaching a certain maximum pressure, and the use of power ceases. Some machines have arrangements which alter the delivery of the pump with the requirement of water, by setting one or more pumps at rest, or by changing the length of stroke of plunger. When an accumulator is used in the system, its motion is used for governing the pump, either by shutting it off just before the accumulator is full or by regulating the delivery as described above. I shall describe only a few of those most commonly used.

457. The Charlottenburg Laboratory has one power pump built by C. Hoppe of Berlin, which, having three plungers, can be operated at different speeds by two belts. It feeds the hydraulic pressure system, leading to all the buildings and rooms of the laboratory, and produces a pressure controlled by a governing plunger, usually of 200 at., but which can be raised to 450 at. (3000 to 6750 lbs. per sq. in.). A safety-valve prevents exceeding this maximum pressure. The pumps are stopped by the governing plunger, by moving a lever when rising when the desired pressure is reached, which supports the suction-valves successively and in such manner that they cannot close again. The water raised re-

turns by the same channel, because it cannot raise the pressure-valves, which are held down by the pressure in the pipes. The working pressure can be changed at will by loading the governing plunger.

458. The Charlottenburg Laboratory is provided with a second automatically regulating power pump, built by Max Hasse & Co., Berlin. This is an intensifier driven by the pressure in the city mains, operating a differential pump, producing hydraulic pressure up to 350 at. The city water acts on the large plunger. The plunger-rod carries a cross-head, which operates the regulation; its prolongation is the plunger of the differential pump. When the cross-head has reached the end of its motion it trips a cock of the valve mechanism. This admits the water from the city main to the cylinder-valve, reversing it rapidly, and thus reversing the motion of the main plunger. It reverses the large water inlet and outlet ports very rapidly, and the reversal of the machine is instantaneous, so that the gauge-indicator on the pressure-pipes drop only from 20 to 30 at. (when running rapidly). A noticeable disturbance of conditions of pressure in the machines is precluded, because the regulating-valves between them and the hydraulic system throttle the pressure considerably; the impact is, however, always noticeable in delicate work. The operation of the pump is strictly proportionate to the consumption of water; when this ceases, the pump stops likewise.

The pressure-pipes are always under the maximum pressure produced by that in the city mains, in proportion to the piston ratio. The machine on the whole has given great satisfaction in the Testing Laboratory, and required very slight repairs; but it was no longer sufficient for the increased requirements, and was therefore replaced by the Hoppe power pump above described. The varying pressure in the city mains especially in summer is a disturbing element in its operation. If steam is available as a source of power, the Hasse type is

decidedly more perfect, because reversal is so rapid that variations of pressure are in no case noticeable, and pressure always remains constant; its operation is very simple and convenient.

459. Wm. Sellers & Co., Philadelphia, Pa., build a very compact, well-designed power pump shown in Fig. 335 (*L 211*). The triple pump is operated by eccentrics and links which can be raised and lowered by a hand-wheel while running. Thereby the stroke of the plungers driven by the links and hence the delivery, have a very wide range of adjustability.

460. Riehlé Bros., Philadelphia, Pa., also build a very compact triplex pump, Fig. 336. Shifting-gears provide for two speeds. The pump is said to have a delivery of ½ gal. at 100 R. p. M. and low gear, and of 2 gals. at high gear per minute; diam. of plungers 1½ in.

460a. Amsler-Laffon, Schaffhausen, Switzerland, build a rotary pump without valves, which draws the oil from a vessel above and forces it into the press-cylinder of the testing-machine. The pump runs at uniform speed, driven by hand or belt, and is designed without packing so as to be self-lubricating in all parts. The pump is stopped by a clutch coupling. The pump is also designed to be driven by an electric motor. Regulation is effected by means of a needle-valve, which controls admission to the press. The oil can again return to the reservoir from the press. The pump requires ½ H. P. for maximum capacity under usual speed with a 165-ton (150,000 = kg) machine. It is shown in Figs. 6 and 7, Plate 14.

461. Pumps similar to those described in (*447–460*) are moreover made by all shops constructing hydraulic plants; it may suffice to have referred to a few examples. Special attention should be given to simple construction, as well as accessibility of valves and regulating devices; duplicate parts thereof should always be provided with a new installation.

2. Accumulators.

462. It will answer to refer to a few accumulators which are in general use, and particularly to those which are used in testing, or are specially adapted for it.

463. The usual form of accumulator consists of a strong vertical cylinder connected to the pressure-pipes, having a plunger carrying heavy weights. Area of plunger and weights are proportioned so that the former rises as soon as the pressure has risen to the desired maximum for service. Increased consumption of water causes the plunger to descend, decrease causes it to rise to its highest position, in which proper mechanism either slows up the pump or stops it entirely. As long as the plunger and its load are kept floating the working pressure in the piping will be maintained. Hence the accumulator absorbs the excess of pump-delivery over consumption by the testing-machine, and supplements the pump when the demand is excessive. The capacity of accumulator, diameter and stroke of plunger, must be suited to the requirements of each individual installation; where there are several testing-machines in simultaneous use, the accumulator may assume considerable proportions.

464. When a low-pressure water-supply is available, so-called multipliers or intensifiers are used instead of loading by dead weight. These intensifiers consist, as in Fig. 337, of a large cylinder 1 and a small one 2. The low-pressure water 4 acts on the large piston 3 and replaces the rising and falling weights of the accumulator. The small cylinder 2 is a part of the high-pressure system 5 as before. The working pressure is dependent upon the low pressure, and the ratio between the two pistons. When the delivery of the high-pressure pump is deficient, then the large piston will be driven by the low-pressure water. When the delivery of the high-pressure pump exceeds the consumption, then the small piston 6 will drive the larger and force the water back into the main.

465. The Charlottenburg Laboratory has an accumulator of the Pohlmeyer type, Plate 9, Figs. 30 and 31, and it is used as an automatic pressure-regulator. Pohlmeyer, however, originally designed it for his machine as a substitute for a power pump. He arranged the piping and valves (indicated in Fig. 337 by the three-way valves 7–9) in such manner that the low-pressure water under the large piston could be drawn off and then opening the low-pressure on the small piston, as shown in Fig. 337. Hence the plunger is forced down, and the accumulator was again ready for the next test. The regulating-valves shown as three-way cocks are to be so arranged that valve 7 connects cylinder 1 with the low-pressure main 4 or with the waste-pipe 10. Valve 8 must either connect the small cylinder 2 with the low-pressure main 4 or with the high-pressure system 5. In the high-pressure pipe just at the machine (especially when several machines are served by the intensifier) a stop-valve as well as a waste-valve 9 (Plate 9, Fig. 30, 73) must be placed, which connect the machine with 5 or with the waste-pipe 11; the former may at the same time serve as a throttle-valve to regulate the speed. When but a single machine is operated it is more convenient to apply this regulation to the low-pressure pipes.

These intensifiers are to be highly recommended for simple and convenient manipulation and especially when a tolerably constant low-pressure supply is available, because they provide a steady source of power, the speed of which can be regulated very nicely. If it is desirable to work rapidly, care must be had that the sections of the low-pressure pipes are not taken too small.

These intensifiers are moreover built by other works, however of somewhat different design, as those of Mohr & Federhaff, Mannheim, Germany (Plate 7, Fig. 6).

466. Latterly accumulators operated by air-pressure are being used successfully, in which compressed air acts on the large piston. These apparatus, as it appears, have some ad-

vantages over those previously mentioned. The Charlottenburg Laboratory will have such an accumulator in its proposed addition. Drawing and description of this arrangement as built by L. W. Breuer, Schumacher & Co. in Kalk near Cologne, after designs by Prött & Seelhoff, are to be found in "Stahl u. Eisen," 1891, No. 1. The scheme of this apparatus is shown in Fig. 338, in which 1 is the small cylinder connected with the high-pressure system. The water-pressure forces pistons 4 and 5 upward, thus compressing the air in 3. Obduration in 3 is effected by means of a layer of oil or glycerine and a cupped leather collar. Chamber 8 is used to replenish the oil. For this purpose cocks or valves 10, 11 and 12 are used, as after closing 11 and 12 the oil from 8 will flow through 10, and then after closing 10 and opening 11 and 12 will pass into 3. By means of piping 9, carbonic acid gas or air can be forced into the cylinder 3 by means of an air-pump (glycerine being substituted for oil when the former is used). This filling need be done but once, after which only the slight loss is to be replenished occasionally. As the pressure of the air must increase considerably when the pistons rise, it is necessary in cases where large fluctuations of pressure are undesirable to increase the air-space by the use of additional receivers 6, connected with the cylinder 3, which can be locked by the valve 7. When making repairs the air is forced from 3 into 6 as much as possible and valve 7 is then closed. When the piston reaches its maximum height the hydraulic pump is closed down. Besides this perforations are provided in piston 4 which act as a safe waste as soon as their orifices pass beyond the stuffing-box. Compressed-air accumulators have been largely introduced in service recently. It is claimed for them that they permit very rapid motion when power is absorbed, and great economy in large masses of material, and operate very steadily and without shock. They also permit the use of various pressures.

3. High-pressure Systems.

467. I have repeatedly called attention to the desirability of large calibre of high-pressure piping, when it is probable that additions are to be made to the equipment, or if it is intended to use viscous materials, as oil, glycerine, or the like. Especial attention must be paid to stanchness of all piping. In the Charlottenburg Laboratory the majority of packings are made as previously described (Fig. 281), by use of rings of lead or leather, which are entirely enclosed. Thus far we have never had a single failure due to this method. Packing by means of steel cones, as in Fig. 280, is especially used under very high pressures when it is desired to change the connections frequently. It facilitates making connections in any direction when using four quadrantal sections. It will also be found in the valve-chamber shown in Fig. 339; I adopted them from Emery's designs. In the Charlottenburg Laboratory low steel (Flusseisen) pipes are in general use; they have given great satisfaction. Within the building the pipes should always be laid in large, easily accessible trenches, in order to be able to make future changes and connections. Small, thick copper tubes are especially useful for movable or portable piping for transmitting high pressure. The Charlottenburg Laboratory has frequently, and during many years, used a soft copper pipe about 100 ft. long, 0.4 in. outside and about $\frac{1}{8}$ in. (10 mm and 3 mm) inside diameter; it has frequently transmitted pressures of 5000 at., and was frequently bent to and fro, rolled up, and occasionally annealed.

4. Valves.

468. Valves in use on high-pressure pipes for sealing them and for regulating speeds of machine give considerable trouble and inconvenience. Knowledge of such constructions which

have given satisfaction in service is, therefore, always valuable. Cocks are very difficult to keep tight, and are moreover not suitable for accurate regulation. I avoid them as a matter of principle.

469. In Fig. 339 I illustrate my design of valves, as it has been developed in the course of years in the Charlottenburg Laboratory, and as it is now used almost invariably.

All valves for each individual machine are placed in one block or chamber, which is mounted on a column in such manner that the levers or handles are about 39 in. (1 m) above the floor. These columns are so situated in the laboratory that they are convenient for manipulation by the observer standing at the telescope of the mirror apparatus, who at the same time should be able to conveniently observe and handle the load-indicator, the recorders, and the test-piece. The chamber (1) is mounted on the cast-iron column by the pedestal (2). The chamber conforms to the tubular shape as much as possible; the passages are not cored, but drilled. It is thus easier to secure solid castings. The seats for valves (3 and 19) are peened by hard drifts before final finish, to harden them as much as possible, and the valve-tips on the spindles are also hammered. These are, moreover, all made of good, tough, dense alloy, because iron wears too rapidly, and hence often becomes leaky.

Whenever possible the water was prevented from pressing against the points of the valves, because in this design the difficulty arose that valves closed but lightly when under regular service pressure, could only be opened with great difficulty when the pressure was released, and the trouble became greater as the length of valve spindle from point to screw-thread increased. The heavy pressure acting against the spindle produces elastic shortening thereof, and hence when the hydraulic pressure is relieved in the system, the spindle forces the valve against its seat; forcible opening is likely to produce

served to make the
as short as pos-
ness. Excessive pres-
valve tightly: fine threads
than coarse, they are more
a relatively coarse thread is
frequently. Besides this,
having small knobs on
of large hand-wheels and
which, although afford-
sitive hold for the hand,
ssive tightening, by causing
operator's attention to his bad
tended for fine adjustment are pro-
eads, and are so constructed that
at infrequent intervals.

Fig. 339, 3 is the main throttle-valve
essure enters from behind the valve.
et 17; 13 and 14 are simple plugs.
xes are usually back of the spindle-
pressure to the regulating-valves. 8
while 10 is used very slow speed and
paratus. This valve is once adjusted
reafter as a rule never touched. To
meddlesome persons, a cap 12 is screwed
ne is unloaded by the outlet-valve 19.
or closed independently of 8 and 10,
need not be touched between tests, and
can always be readily obtained. The
connections is secured by use of conical

nes at the Charlottenburg Labora-
with the city water mains as well
ssure system, in order that all machines
city pressure when running light. For this

purpose a pipe carrying city water is brought to the valve-pedestal, and is provided with a three-way cock connecting it with the outlet-pipe 17. Upon opening the valve 19 and according to position of the three-way cock, the machine may be either driven or relieved.

471. I constructed the regulating-valve shown in Fig. 340 ($\frac{1}{8}$ size) for the Charlottenburg Laboratory, which has the object of varying the water-pressure in a vessel to be tested (pipe, iron flask, pressure-cylinder of a testing-machine, etc.) automatically between a maximum and a minimum pressure.

Problems of this kind arose in the laboratory during repetitive tests of carbonic-acid flasks, which had to be charged and relieved alternately many thousand times. The proposed tests of steam-pipes under frequently varying pressures and simultaneous changes from hot to cold will require similar arrangements.

The construction of this regulating-valve for frequent reversal of pressure is briefly described below.

The valve-body 1, Fig. 340 *A–E*, is connected to the admission-pipe and the vessel to be tested by the pipe 16. If a number of vessels are to be tested in an identical manner simultaneously, they are all to be connected by pipes 14, each controlled by a valve 13. In the chamber 1 there is a neatly ground piston 3, which transmits the increasing pressure by means of the spring case 5 and the levers 6 to the regulating springs 7 for the maximum limit of pressure. The piston is connected to the reversing-valve by a prolongation. The valve will thus be tripped for discharge (release) as soon as the pressure back of the piston has increased to such an extent that the nut 12 originally bearing against the valve-body is raised by a certain amount. This will relieve the pressure in the vessel to be tested. As the reversing-valve is so constructed that it will at first remain in its position while the piston recedes, the nut 12 will again become seated on 1 during decrease of pres-

sure. The piston 3 can then advance in 1 only when the pressure in the piping has decreased to such an extent that the regulating-spring for minimum pressure overcomes the liquid pressure. The slight play of $\frac{1}{4}$ in. (6 mm) which the spring 10 allows the piston suffices for the reversal of the reversing-valve, and then the operations are repeated. The adjustment of springs 7 for the maximum pressure is made by detail 8 and 9. Spring 10 is adjusted for minimum pressure by screw 11.

The construction of the reversing-valve is shown in Fig. 340 *F–H*. In the valve-chamber 17 there are three annular slide-valves 18–21 moving with each other, of which 18 is connected to the piston and moves with it. Slide 19, 20 is a valve composed of two pieces which is moved by 18 only after the latter has travelled the distance desired, which can be regulated by adjusting-nuts. 21 is the actual reversing-valve, thrown suddenly by the water-pressure to either end of its stroke when the drag-slide 19 admits the high pressure (duct 35 or 36) to slide 21.

When piston 3, Fig. 340, *F*, forces slide 18 to the right, when maximum pressure has been reached in the vessel to be tested, it will first close openings 32 in the slide 19. If 18 travels so far to the right as to open passage 35, the pressure in duct 27 will throw slide 21 to the right, permitting the water from 36 to escape by 33 and 34. This motion of 21 at the same time opens connections between passages 30 and 31, and the pressure water escapes through pipe 16 and valve 23 to pipe 25. Valve 23 serves to regulate speed of release.

If piston 3 forces the drag-slide 19 to the left when the minimum pressure is reached, until passages 36 and 28 become connected, the slide 21 will be thrown to the left. Passage 31 becomes connected with 29, and the pressure in 24 is admitted to the object under test by means of valve 22 and pipe 16. The pressure increases at a rate controllable by valve 22. Then the operation is repeated. Screws 26 lock the drilled holes, or can

be used as connections for gauges. Pipe 35 is the outlet for the tripping-water escaping by 34.

All holes are bored by machine, and the passages are milled. The inlet valves and valve-passages are made ample, in order to allow the use of oil or glycerine occasionally. This is especially necessary for the operation of repetitive test-machines, constructed according to the Amsler-Laffon (Amagat) design, having ground pistons without counterbore (*477*), and which is so arranged that it can be used equally well for tension, crushing, and also alternate-tension-crushing tests. In the latter case a special reversing device must of course be provided for the change from tension to crushing, or the regulating device must be provided with the necessary passages.

In similar manner the arrangements for pipe-tests, under changes of pressure and temperature, may be provided for.

Simple reversing valves of the foregoing type are very successfully used in the Charlottenburg Laboratory for various purposes, as, for instance, the automatic adjustment of poise-weights on testing-machines (*524*), and hence perfect success may be expected of the device above described.

Other arrangements of valves shall be discussed with the testing-machines or shown in the drawings.

5. Hydraulic Cylinders.

472. The following general remarks may be made about hydraulic cylinders:

They are usually made of cast steel or iron, wrought metal being rarely used. Pistons are frequently cased in brass or copper to prevent corrosion due to acid in water or lubricants. Cupped leather collars are generally used for packing, which, when carefully made and used, serve admirably; they may be made so tight that after years of use not a single drop of water will leak from them. This is a requirement absolutely necessary for testing-machines when mirror apparatus is to be used.

Stuffing-box packing of hemp, etc., is rarely used, especially in case of high pressure.

473. A very large machine, whose piston is packed with hemp, is that designed by Chas. Kellogg at the Union Bridge Co., Athens, Pa., shown in Fig. 315 (*445*) of 600 t. capacity (*L 48*, 1887, I, p. 413; *42*, 1887, p. 1). The construction of cylinder 1, cylinder head 2, and piston 3 is shown in Fig. 341. These three parts are made of cast steel. The four piston-rods 5, each of 5⅝ in. (145 mm) diameter, pass through stuffing-boxes in the head packed with hemp, while the joints between cylinder and heads of this powerful machine are packed by copper rings.

474. A still larger machine of the same pattern of 1200 tons capacity is that of the Phœnix Iron Co., at Phœnixville, Pa. (*L 48*, 1891, p. 142). It has a piston of about 64 in. (1630 mm) with 4 pistons of about 8½ in. (216 mm) diameter. Hemp packing was selected because it was assumed that this water-soaked packing would produce much less friction than cupped leather packing, and slight friction was essential because loads are not weighed by a scale. The load applied is determined by gauge-reading.

475. The large 1200-t. Kellogg machine at Phœnixville, Pa., having a diameter of piston of 64 in., is operated by hydraulic pressure up to only 60 at. In this case the hemp packing may perhaps remain sufficiently tight to carry out crude tests; but for tests requiring measurements of precision, in which the packing must be absolutely tight, it is probable that only the cupped leather or ground piston (*477*) are applicable.

The question, however, as to the amount of friction in packings, plays a very important rôle in hydraulic testing-machines in which loads are determined from gauge-readings of the hydraulic pressure in the straining-cylinder. But as this type of machine, because of the great simplicity and absence of all complicated and delicate parts, is

of great value in actual practice, I shall here impart what I found in literature in regard to friction of packings. I should be very thankful to my readers for the communication of further facts, and hope that the Charlottenburg Laboratory will have an opportunity to increase the results of observations.

By means of a low-steel column the great Phœnixville machine was compared with the famous Watertown, Mass., machine.* The same roller extensometer reading to $\frac{1}{10000}$ in. (0.0025 mm) was used for reading the amount of crushing. The gauge-readings of the Phœnixville machine gave results of from 15–17% greater value than were obtained with the Emery machine, and this difference is ascribed to friction and error of gauges of the Phœnixville machine. After applying the above correction of 15–17%, it is considered that the errors in the results of the Phœnixville machine will be within 3% of those of the Emery-Watertown machine. (It would be valuable to know the degree of certainty with which this comparative factor may be assumed to remain constant.†) (*L 257*.)

476. Tests of friction of cupped leather collars were made by Marié (*L 212*).

The conclusions of tests made by Flad, and published by Cooper, are plotted in Fig. 342 (*L 213*). Henry Flad made his tests with the apparatus shown in Fig. 343. The cylinder 1 was packed by two cupped leather collars 3, surrounding the piston 2.

Flad gradually decreased the width of a collar, bearing on the piston from $1\frac{1}{8}$ in. (28 mm) to $\frac{1}{8}$ in. (3 mm); hydraulic

* These comparative tests were suggested and inaugurated by the translator, and another series of observations (not given in *L 257*) were made by him, using his own extensometer, with practically the same results. The errors of the Phœnixville gauges were in no case determined. In each series of tests, however, measurements were made on one side of bar only.

† A similar comparison made by the translator three years earlier gave similar results.

pressure was admitted by pipe 7 and measured by the gauge 6; it was raised to 30 at. The force P required to move the piston 2 under various pressures was then determined. This force, expressed in % of the total pressure which a piston of diameter d would exert under the various hydraulic pressures used, is plotted in Fig. 342 in A and B, arranged for increasing pressure. The influence of the condition of the leather collar is seen, as well as that of the diameter of the piston. The friction amounts to 1% at high pressures.

For pressures up to 400 at. Hick (*L 214*) showed the piston friction to be less than 0.5%. Compare Fig. 342, *C*.

Friction of Leather Packing in Hydraulic Presses.

(Trans. Am. Soc. C. E., 1887, p. 30.)

1-3 diam. piston ½ in; 1, new and stiff leather; 2, much used; 3, new leather.
4, 5 " " 4 in.; 4, new and stiff leather slightly greased; 5, well treated and lubricated.
6, 7 " " 8 in.; 6, " " " " " " 7, " " " "
8 " " 9 in.; 8, 16 tests with cupped leathers of various widths.
9 " " 6 in.; 9, 24 " " " " " " "

In 8 and 9 full lines give averages; maxima and minima, fine lines.

Nos. 1-7, Hick's tests; Nos. 8 and 9, Flad's tests.

Nos. 4-7, friction decreases constantly with increasing pressure, and is less than ½% for n = 400 at.

477. Amsler-Laffon avoids all packing in his testing-machines, Plate 14 and Fig. 133 (*453*), as he follows Amagat's principle of fitting the piston into the cylinder with such accuracy that the viscous castor-oil used can pass the joint between piston and cylinder only very slowly. This construction is also satisfactory, as it demands perfect, positive, and long guides of the piston, (*603*, *b*). In order to produce good work, Amsler-Laffon leaves his cylinder 16, Fig. 333, open at both ends; large boring-bars can thus be readily used. The piston, which may be said to be floating in a slowly flowing layer of oil, has in fact very slight friction, especially when at the same time constant rotary motion is produced, as is the case in the pressure-reversing pistons 26 and 3, Fig. 333A. This piston is given an oscillatory-rotary motion by the eccentric 35 and links 28 and 30.

b. Mechanical Loading Devices.

478. Mechanical loading (as distinct from hydraulic) is usually done by screw and worm-wheel. Screw mechanisms are, of course, constructed in many different forms, but as they are special forms of machine construction I shall not further discuss them; it will be easy to understand the types used in testing-machines without special description from an examination of the many illustrations on Plates 3–20.

The worm-wheel is either driven by hand or by shafting. In the latter case the construction differs, as it may be provided with various speeds, or with rapid-return motion. I shall mention but a few types here.

479. Mohr & Federhaff provide a friction disc on a counter-shaft, Plate 6, Figs. 3 and 4. The various speeds are obtained by shifting the small wheel 31 with reference to centre of large wheel 30 by rope-drive and screw 32. The speed can therefore be arranged at will, only limited by the diameter of the large wheel.

Other examples of very complicated designs are shown on Plates 4, 8, 13, 14, 15, 16, 18, and 20. Among these I wish to call particular attention to the combination of hydraulic and screw power in the Gollner machine Plate 13, Figs. 1–5, and to the peculiar drive by wedge-surfaces of Chamond, Plate 15, Fig. 15, hardly worth imitating.

480. If the question arises as to the advantages of hydraulic or mechanical power, we may reach the following considerations:

For small forces the screw power is no doubt the more convenient under all circumstances. Especially as long as the power necessary can still be easily supplied by the hand of the observer, hydraulic power will hardly be used in case of individual machines. Even when shafting is available for power and but a few light machines are to be operated, screw power is more desirable, which is provided with convenient

devices, such as the Mohr & Federhaff driving mechanism (*479*, Plates 6 and *7*). If, however, heavy power is required, screw power becomes inconvenient, and hydraulic pressure will be the simplest. This is also true for small machines, in case a pressure system is available, or a system may be provided for several machines. Hydraulic power offers so many advantages and conveniences under these conditions that it is to be preferred to screw power.

Advantages claimed for screw-power are steadiness of motion, freedom from impact, and also the fact that any and all loads may be left indefinitely on the test-piece without danger of drop of load other than that due to the change of shape produced. For measurements of precision this is, of course, a great advantage. This requirement is, however, a rare exception in testing-materials, which may be necessary, however, in scientific laboratories. As a rule, the cupped leathers of hydraulic presses may quite readily be put into such condition that there is hardly any leakage, so that hydraulic presses will also maintain loads for long periods of time without requiring replenishment; this does certainly, however, require superior maintenance of the machine. There is, then, no difficulty whatever in making precise measurement with mirror apparatus at leisure. Loading by hydraulic pressure, the speed may be varied most conveniently between wide limits when suitable valves are provided (*469*), Fig. 339.

481. However the driving-power may be arranged, the principle that the operation should require as few attendants as possible, and that, if possible, the operator should be able to handle all detail, so as to have the machine completely under his personal control, without having his attention withdrawn in any manner from his other duties, should always be borne in mind. All manuals (valves, levers, loading devices, etc), should move freely, and be most conveniently accessible.

c. The Frame.

482. The frame has the first essential duty of transmitting the loads produced by the loading mechanism through the test-piece, thence through the indicating mechanism and back to the loading device, hence to close the circuit of forces. Its second duty is to hold the whole in place, hence to transmit all loads and external forces to the foundation as well as to absorb the shock produced at the instant of rupture and make it harmless. Its third duty is to correctly guide and serve as abutments for the mutual motions of parts of the machine, and to provide points of support for auxiliary apparatus, measuring-instruments, etc. All these requirements make possible a great many different designs, which are partly predetermined in advance by the general construction of the machines (*439*, etc.), but are dependent to a great degree upon the skill and knowledge of the designer. It is in itself not always very easy to divine the ultimate ideas of the constructor of a machine, and with the great number of possibilities it is much more difficult to embody the fundamental principles of construction in definite shapes. For these reasons I cannot enter upon a discussion of the details of the frames of machines, and must limit myself to a few general remarks, illustrating them by a few examples.

483. The first stated principle of complete circuit of forces is made exceedingly clear by the Emery testing-machine (*L 211*) as built by Wm. Sellers & Co. of Philadelphia, Pa., Plate 18. The large left-hand cylinder, Fig. 344, conceals the weighing-chamber (*559*), while the straining mechanism (hydraulic press) is at the right-hand end of the machine, the two being connected by the two heavy shafts. The whole is carried by two legs which appear relatively light, as these merely carry the dead weight and transmit some of the

forces of inertia produced by rupture of test-pieces to the foundation. The machine is used for tension- and crushing-tests, and hence the shafts are subject to crushing in the first case and to tension in the second, the circuit of forces being thus made in the simplest manner. The forces in the frame are transmitted in the most apt manner. For, only two bending moments act upon the massive cast blocks, having a very great moment of resistance transmitted to the cylinder and upon the casing of the weighing-chamber.

In considering the frame or base of the machine it must never be forgotten that even very massive parts ultimately show deformations under stress (be it ever so slight), and these may become very annoying under certain conditions, when not foreseen or provided for in the design of the machine. I have discussed such a case most fully in the description of my 50-ton machine (*L 162*).

In order to present these conditions to students most strikingly they must determine flexure and other deformations of individual parts of the machine, if necessary by use of mirror apparatus, during their regular work in the laboratory. The flexure of the long lever-arm of the Werder machine was, for instance, found by measuring the distance of its end from a straight-edge mounted on the main body of the lever when light and when loaded. It was found that the greatest load on scale-pan (450 lbs.) produced a deflection of about $\frac{1}{8}$ in. (3 mm). Fig. 345 shows the measurements plotted for loads from 0 to 440 lbs. (0–200 kg) (100 tons capacity). The heavy full line shows results of rough measurements with millimeter scale, the fine line those of the cathetometer under increasing loads; broken lines under decreasing loads.

The possible effect of deflection of parts of a machine on the accuracy of a weighing-machine, even when unloaded, is demonstrated by the following examination of the Werder machine.

In a special series of tests the scale-beam was made to float at 0 while the piston was completely within the cylinder, when it was gradually moved out, without changing anything at the scale, and the new point of equilibrium was found for different positions of piston, by use of the spirit-level and usual methods. Fig. 346 represents the change of equilibrium for various positions of the piston while moving in or out of the cylinder. Readings of scale on level (means of readings at both ends of bubble) are plotted in vertical direction, while piston positions are plotted horizontally. These displacements of point of equilibrium are probably partially due to the deflections of the supports 4, Plate 3, Figs. 2 and 3, of the sled 9 which carries the plunger and the scale. As the resultant of weight of the supported parts shifts as much as the plunger, there must be deflection of the support (although very slight). But this

cause alone does not account for the behavior of the beam, for repetitions of the test always show changes of position of equilibrium, but the sequence of these variations changes more than would be the case if produced by a single cause.

These facts are certainly very instructive and urge a much more exact investigation of our machines than is commonly made.

Gollner examined his machines most critically (*L 220*); he found an error of 1% at 44,000 lbs. (20,000 kg) load. Influence of deformations and of inaccuracy of workmanship has been also demonstrated in (*L 215*), which gives my investigation of sources of errors of the small Hartig-Reusch paper-tester, Plate 11, Figs. 1–13. In the description of my 110,000-lb. (50,000-kg) machine (*L 162*) a very characteristic case of flexure and influence of deformation of a very heavy frame has been fully discussed and its effects elucidated.

484. It is an important question whether a machine is to be built horizontally or vertically. The decision of this question besides determining the shape of machine also exerts a material influence on the development of the frame.

In general the vertical type is to be preferred, because the secondary stress produced by weight of test-piece is avoided, i.e., the bending-stress of columns under crushing- and thrust-tests. But the vertical arrangement is only possible in case of relatively short machines, unless elevators for the observer (Bauschinger's vertical machine) are to be used.

Tests of very long pieces require horizontal construction. This is generally very readily observable, accessible, and handy, but produces the necessity of guiding, supporting, or suspending all parts which must remain movable, because otherwise secondary stress would be produced in the test-piece.

485. The frame of the machine should be designed so that the test-piece, the weighing and the loading mechanism are clearly visible and accessible. The exchange of holding-devices and bearing-blocks for different kinds of tests must be convenient. It should be possible to remove stuffing-boxes without partially dismantling the machines. Examination of the Sellers-Emery machine shows that

many advantages may be gained by carefully observing the main requirements. Sellers build their heavy machines* the same as many other designers (Werder, Kellogg, Hoppe and others, Plate 3, 10), horizontally, so that the straining-screws lie in the horizontal plane passing through the centre line. In this case they can really be used only for tension- and crushing-tests, and also perhaps for punching and shearing, etc, for which the auxiliary devices have space between the straining-columns. These machines are, however, of little use for reasonably large pieces under bending-stress. This would be a very easy matter, even with very large pieces, if the two columns were placed in the vertical plane through the axis of machine, which would be a relatively simple matter in the Sellers machine. In this case it would be easy to make transverse tests of girders and similar pieces in a horizontal position, and convenience and accessibility of other tests would also be materially enhanced. The Wicksteed 100-ton machine, Plate 17, Fig. 7, is similarly arranged.

The monstrous shapes which vertical testing-machines sometimes take when the weighing mechanism is placed on top of the machine is shown by a comparison of the Wicksteed, Pfaff, and Martens machines (Plate 16, Figs. 11 and 12; Plate 13, Figs. 15–17; Plate 5, Figs. 1 and 3). Each has a single lever, which in case of the Wicksteed machine is very long and carries a travelling poise. The lever of the latter assumes monstrous proportions. An inconveniently heavy mass which cannot be nicely proportioned and requires a number of details which by no means help to beautify it (beam support at end of lever to receive the impact at instant of rupture, mechanism for operating the poise-weight) floats above the head of the observer. In the two other machines, that of Pfaff, also having a capacity of 220,000 lbs. (100,000 kg), has a lever of very high ratio, and relatively short levers with drop-weights. The lever-masses become smaller and may more readily harmonize with the other rigid parts of the machine.

In face of these circumstances the question must be asked whether the capability and accuracy of this unshapely Wicksteed

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* Sellers build all of their machines horizontally because it is claimed that otherwise shock at instant of rupture is liable to injure the machine. A few machines have been built with the plane of axes of straining-screws at an angle of 45° with the horizontal.

machine excels the other two to such a degree as to warrant such a type of construction? This is not, however, to be interpreted as meaning that the Wicksteed does not possess advantages, for I refer in this case to exterior appearance alone; but the question of the inertia of masses cannot be entirely suppressed, especially when it is stated that tests are made with this machine in 1 or even ½ minute. More attention should, moreover, be paid to inertia in case of other machines.

C. The Load-indicator.

486. The same principles which apply to scales, gauges, etc., also apply to the load-indicators of testing-machines. There are some additional special features which have individually been adopted more or less generally in testing-machines. The scale, especially the beam-scale, is frequently such a predominant feature in the design of a testing-machine, that it becomes apparent at the first glance in the modern machine. I refer to the machines of Mohr & Federhaff (Pl. 6 and 7); Riehlé (Pl. 19); Olsen (Pl. 20); and Fairbanks. The latter uses a scale with very many levers, which reminds one very much of the ordinary platform scales. In the United States I saw but two examples of the Fairbanks machine; as it no longer appears to be built, the present reference to its construction shall suffice (*L 45*, Febr.; *12*, 1884, p. 84, 113).*

I have already classified the types of load-indicators in (*65 a–g*). Here I shall examine the character, the requirements of construction, and the peculiarities of load-indicators more thoroughly. I shall, however, treat the subject very broadly, and as a rule refer to but few examples. The detail, where deemed necessary, will be described in connection with the individual machines, or be left to a study of the illustrations.

* The Fairbanks machine never having been satisfactory, has not been built for ten years or more. It is difficult to say which was more defective: its design or construction.—G. C. Hg.

a. The Lever-scale.

487. The principle of attaching the knife-edges to the levers and their bearings to the frame of machine is generally observed in the design of lever-scales having fixed lever-ratios. The design should, however, be so arranged that lever-ratios may be readily calibrated either by direct measurement or by weighing.

488. The accuracy may be made very great even in scales of great capacity. But in testing machines they must not only be able to carry steady loads, but also capable to withstand impact and oblique loads. Impact occurs whenever rupture takes place; oblique loads may arise under crushing test in tension tests of wire rope when the machine is not so arranged that the holders can transmit the torsional force to the frame, or adjusts itself to it. In the Werder machine (Pl. 3), for example, it has happened that one knife-edge 20 left its seat 19 in the cross-head 21 (Fig. 4) when testing a very strong wire rope under effect of the torsional moment, because the screw 24 (Figs. 1–3) had been drawn up too tightly. The scale should hence be so constructed that none but the forces to be weighed can be made to bear on it. I refer to this particularly because this requirement, which appears self-evident, is not always provided for. Displacement of the knife-edges on their bearings must also be guarded against, so that the faces of levers may not produce friction against the frame. Even the safety devices to provide against possibility of displacement of knife-edges on their bearings have been improperly designed by prominent manufacturers, and I have had occasion to call their attention to this almost incredible error while calibrating testing-machines.

In order to show that details may become very questionable in the hands of unreliable operators, even in machines which are in almost universal use, I call attention to the Riehlé and

the Olsen machines, Plates 19 and 20, in which the upper part of the machine, the platen supporting the columns and upper cross-head, is connected with the base of the machine by four bolts. These four screws are to prevent the platen from jumping at the instant of recoil, and the knife-edges from leaving their seats (*526–528*). For this object thick rubber washers (buffers) are placed under the nuts. It is not impossible that tightening the nuts may affect the results of tests, and when using different machines it is necessary to determine the tightness of these nuts.

489. That great value should be laid on great rigidity of levers, without, however, passing beyond a practical degree, will be understood from statements in (*483* and *503*) without further discussion.

490. Some designers have laid great stress upon proper balancing of levers, and hence have provided them not only with counterbalance-weights, but also with poise-weights so as to provide adjustment of elevation of C. of G. with relation to centre of oscillation, as Gollner, Pl. 13, Figs 1–14. Without doubt the weighing system is improved thereby, but it is a question as to how much of it is necessary, and actually becomes effective. The load-indicator in the testing-machine is a vibrating balance only solong as the machine is loaded. As soon as the test-piece is fixed, oscillations can occur only because neither the test-piece nor the machine is inelastic, and both are moreover materially affected by the inertia of the masses of the members of the scale. I imagine that under these circumstances accurate adjustment of the scale is of little importance (by no means denying the convenience and other advantages), and that far greater benefit is derived by the greatest possible rigidity of the levers. For, instead of initial adjustment to zero, it would be just as correct to take an initial reading or to adjust the scale to a zero reading by shifting. This idea is in fact frequently adopted in machines with pressure-gauges, reducing-chambers, etc.

Adjustment of sensitiveness, and its determination by initial

vibration or under direct loading by weights, is ultimately of doubtful value, and in fact only a convenient method to determine whether changes of condition of the machine have occurred. For this reason and others (*534, f, 595, i*) I have introduced Bauschinger's method (*L 217*) of the standard bar for calibrating the machines in the Charlottenburg Testing Laboratory. Direct loading (or the use of the calibrating scale) is used in connection therewith for determining lever ratios when unloaded or under very small loads (*534, a–l*).

491. Much has been written as to whether a lever of very high ratio or many levers with relatively great lengths of arms are preferable in a testing-machine. After the foregoing I need hardly state, that both methods may produce satisfactory results, as proved by the great distribution of both types of machines. It is my personal opinion that machines with many levers merely follow the custom of scale-builders, probably without much profound thought, and hence again call attention to the external character of many machines. When it is considered what is stated in previous and following sections, it will be understood that I give preference to few levers with high ratios, because skilful application will lead to simpler and more convenient types, more easily watched and handled, which are generally materially more rigid, than scales with many movable members. Ultimately, however, such design of load-indicator which insures the degree of accuracy stated in (*506*) with reliability is always sufficient, and this may be reached by a single lever as well as by the use of many.

492. In order to show a few additional peculiarities in lever arrangements for load-indicators, I call attention to the machines of Mohr & Federhaff and of Grafenstaden, Pl. 6, 7 and 8, in which differential levers as shown in outline Figs. 347 and 348 are used. The original Riehlé machine was also similar to Fig. 348. The design of the load-indicator in the Gollner machine is very complicated (Pl.

13, Figs. 1–14), especially on account of the reversal of power for different kinds of tests (*598–601*) (*L 220*).

The lever systems of Riehlé's (Pl. 19) and Olsen's (Pl. 20) machines are shown in Fig. 414 (*525*) in conventional sketches. The scheme of Hoppe's scale is described in (*591*) Fig. 417.

2. Knife-edges.

493. The detail construction of knife-edges and their bearings on levers of testing-machines is of some importance, and, as but little has been published on this subject, I shall give some notes.

The first question that arises is, how heavily may a knife-edge be loaded? Rules for design thereof are unknown to me, hence I mention some practical cases. In the Werder machine (Pl. 3, Figs. 1–3) the main knife-edge 17 is about $13\frac{1}{2}$ in. long; the lateral knife-edges are each about $7\frac{1}{4}$ in. long. Hence each inch of edge carries about 16,000 lbs. (2900 kg per 1 cm) and 15,000 lbs. The extreme edges have suffered a visible flattening during the course of years under the numerous tests at the Charlottenburg Testing Laboratory, and on the somewhat soft bearings, traces of depressions, and wear are quite noticeable. Estimating the surface in contact between knife-edge and bearing on a liberal basis as 0.0195 in. (0.05 cm) wide, then the stress will equal 381,000 lbs. per sq. in. The actual maximum load is most likely rather greater than less than this figure, but nevertheless the machine has given general satisfaction during its many years of use. The middle knife-edges 8 and 13 of the 110,000-lb. Mohr & Federhaff machine (Pl. 6, Fig. 2) carry a load of 55,000 lbs. on a length of $3\frac{1}{2}$ in., or about 15,714 lbs. per in., or about 44,000 lbs. per sq. in.; the main knife-edge of the principal lever 15 of the 110,000-lb. Pohlmeyer machine (Pl. 9, Fig. 2) is loaded to about 54,000 lbs. per sq. in., and in the Grafenstaden (Pl. 8) the load may be even higher. In the 500-ton Hoppe machine (Pl. 10) the

load on the principal knife-edges may be about 49,700 lbs. per sq. in. Most of these machines have been built in considerable numbers and have given great satisfaction; hence the conclusion may be drawn that stress on knife-edges of 57,000 lbs. per sq. in. is practically permissible; this stress will certainly not be permitted unless necessary. Gollner states the stress on the knife-edges of his machine (Pl. 13, Figs. 1–14) to be 370,000 lbs. (= 24,600 at.).

494. Knife-edges should be secured in the levers in such manner that they can be readily ground straight and parallel to each other, when in position. This condition is generally difficult to meet; as a rule the end knife-edges dovetailed in the levers are so constructed (see Pl. 8, Fig. 2, lower levers 3 and 4; Pl. 6, Fig. 1, levers 7 and 12). The middle knife-edges usually pass through the lever, and are ground at the ends, while they have a central rectangular section. These knife-edges are sometimes merely inserted with a driving fit. With such construction it should not cause surprise if the knife-edges loosen in course of time under the effect of heavy shock at instant of rupture, especially when deep knife-edges are fitted to thin levers.

495. Werder placed great weight upon good construction of knife-edges and of bearings. For this reason I adopted his method for my 500-ton machine, and refer to Pl. 5, Fig. 10, because this shows the detail better than Pl. 3, Fig. 3, parts 17 and 18. Werder bedded his knife-edges in heavy cast blocks, to prevent any possibility of bending, and supported these blocks on flat planed surfaces on the levers, to which they were securely fastened by angle-blocks and screws. The knife-edges are secured in their bearings by bevelled liners (Fig. 10, Pl. 5, 18 and 19). The two lateral knife-edges 20, Pl. 3, Fig. 4, may very easily be brought into a position truly parallel to the upper planed surface of the heavy casting 13 of the scale by means of the adjusting cheek-pieces, so that they lie truly in a straight line, as the edges can be ground

parallel to the bearing-surfaces of these bodies. The middle knife-edge is similarly ground, so that when its bearing-block has a full bearing against the vertical face of the lever 13, it lies accurately in the plane passing through lateral knife-edges 20, normal to the upper surface of 13. The middle knife-edge 17, Fig. 3, may then also be easily adjusted accurately parallel to the upper surface of 13. Werder originally provided means for accurate adjustment, so that the distance between the planes passing throught the middle and lateral knife-edges could be adjusted accurately, i.e., the lever ratio could be made $= \frac{1}{500}$, which was done by means of a calibrating scale. This adjustment of the short lever-arm was always very difficult, and I therefore firmly fixed the middle knife-edge, and thereafter used the adjusting device 15, Fig. 1–3, attached to the long lever.

496. Pfaff used a peculiar form of adjustable knife-edge seat (Fig. 349; L. Mach. Out. 1890, p. 81). He mills the knife-edge out of a solid rolling-cylinder 1, and fastens the latter by use of the tangential bolt 2, in the lever. The adjustment of leverage is secured by the thread on 2 engaging a thread in the cylinder, which is then clamped in position by the plates 3 and 4.

497. The advantage of the Werder lever construction will be seen to be the possibility of adjusting the leverage to the smallest length desired; hence angle-levers of great ratio can be readily obtained. Another advantage is the massive rigid lever-block, which is excellently adapted to transmit bending moments from the main knife-edge to the lateral knife-edges without transmitting any noticeable bending of its own.

498. The lever of my 50-ton machine (Pl. 5, Figs. 1–3) is constructed on the same principle; it forms a straight two-arm lever of ratio $\frac{1}{250}$. The construction is self-explanatory when it is noted that the extension to the left, the lever 25, with counterbalance 26, is a system by itself. The poise-

weights are deposited mechanically, the weight-disks being raised or lowered by screw 37 to 39 by means of a hand-wheel, one after another, and placed upon the suspended scale-frame 29. When deposited they rest upon the nuts on the bars 36. Each disc 30 represents a load of 2,200 lbs. (1,000 kg). Disks 31 represent loads 22,000 lbs. (10,000 kg); they are operated by the crank 43.

499. I used a similar construction for my small 5-ton machine (Pl. 13, Figs. 18–31). The detail of lever construction is shown in Figs. 25–31; adjustment of middle knife-edge makes it possible to obtain a high ratio (*L 258*).

500. I have used another construction of levers of high ratio in the design for the scale of the large torsion machine for a torsional moment of 1,887,600 in.-lbs. (2,200,00 kg 1 cm), for the Charlottenburg Testing Laboratory (Fig. 350). The lever 3 serves as a support for one end of the arm 5, which holds the test-piece. The main knife-edge is fitted rigidly in the fork of the lever, while the pair of middle knife-edges is secured to the slide 4, which, bearing on projections on the lever-block 3, can be so adjusted and clamped that the short lever-arm of 3 may be of any length. It will be noted that the knife-edges are so fitted to their seats that they can be readily ground truly parallel to each other on a grinding-machine. The lever ratio is $\frac{1}{200}$.

The action of the scale is shown by Fig. 351, in which identical numbers correspond with identical parts in Fig. 350. The forces P of the torsional moment are transmitted to the scale and the other to the foundation by frame 15 and bolts 17 (Fig. 350). The scale is composed of the levers 3 and 6 and the rolling-poise 7. It can resist right- and left-hand moments—left-hand moments in position shown, and right-hand moments when the entire scale is swung 180° about its pivot 19 and secured by the four other anchor-bolts 17. The foundation, 8.4 ft. (2.5 m) deep, rests on a continuous iron bed-plate. The machine is built by E. Becker, Berlin.

3. Plate-fulcra.

501. The heavy stress put upon the knife-edges is referred to in (*493*); they are easily injured, and it has therefore been suggested repeatedly to abolish them altogether. Emery's method is the particular design to be examined. He very skilfully replaced the knife-edge (before 1874) by a plate-fulcrum, which had already been used before him in Germany* in fine physical balances, but had been again abandoned.

502. The details of Emery's design of scale-levers are shown in Figs. 352–354. Figs. 352 and 353 show a few examples of beam-connections under tension. Fig. 354 shows the "head" of a platform-scale in which the plate-fulcra are some in tension and some in crushing. In this case the unsupported parts of plates 4 and 6 are very short and clamped in stiffening-blocks, so that all bending is confined to a very small part. The load to be weighed is transmitted by the column 3 resting on an Emery pressure-chamber (*559*) by means of fulcrum 4 to the real, heavily built lever 5, the end of which carries disks at 11, representing larger loads than those marked on beam. This series of weights is consecutively deposited on brackets on 10, by raising and lowering the weight-frame or basket 1–3. The indicator 8 supported at 7, Fig. 354, shows the play of levers on a largely magnified scale on the reading-scale 9, so that the motion of lever 5 need be only minute. The sensitiveness of the scale may be regulated by weight 12. 13–16 are sliding poises, of which 14 and 16 are used to balance the beams. Spring 17 counteracts the weight of column 3, which is guided in rectilinear motion on top and bottom by Emery's system of plate-connectors. Latterly Wm. Sellers & Co. are

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* I found that Avery (Birmingham, England) as early as 1852, and a mechanic in Vienna, Ferber, in 1847, had used plate-fulcra in scales, but in both cases failure resulted from lack of knowledge of principles and mechanical skill.—G. C. Hg.

using somewhat modified types, details of which, unfortunately, are unknown to me.*

503. The use of plate-fulcra in the construction of a weighing-machine for a testing-machine has the undoubted advantage that provision against lateral displacement of joints can be made in a simple, reliable manner (*488*), and that shock at instant of rupture has little influence on the condition of the scale. But I believe that even these advantages will not effect the general introduction of plate-fulcra in testing-machines. On the other hand, I have the conviction that the Emery "supports" (pressure-chambers) [and those of other constructors] (*554–563*) will be introduced more and more generally, as soon as simple and reliable means for calibrating testing-machines are available (*504*).

504. I expressed my views on the importance of plate-fulcrum connections for scale construction, and especially for that of testing-machines, in an unpublished report of a professional visit to the United States, and in my description of the Sellers type of Emery machines (*L 211*). From the latter I take the following extracts:

Some time ago the Emery system of plate-fulcra, as a substitute for knife-edges, received an enthusiastic laudation by Reuleaux (*L 216*). Even at that time I had my doubts about the vaunted superiority of the plate-fulcrum, and have to this day been unable to dismiss my doubts, although I have now had occasion to make my own observations on numerous machines in the United States. However, not to mislead the reader by subsequent statements, I wish to premise that my doubts are still of a subjective character, because a measuring-apparatus or testing-machine can be reliably criticised only by one who has had opportunity to use them personally, to determine the degree of their errors, or by him to whom sufficiently exhaustive series of tests, the reliability of which can be proven, are accessible. These opportunities I have not had.

The excessive sensitiveness of the Emery scale, and the necessity of housing it in a separate case, awkward for a testing-ma-

* Wm. Sellers & Co. do not construct any scales whatever; they confine their work to horizontal testing-machines.—G. C. Hg.

chine, Fig. 356, make it necessary for the observer to bestow his undivided attention on it. As the scale does not approach equilibrium steadily and quietly, it requires constant attention; as long as the press is moving, the operator cannot for an instant neglect the levers used for depositing poise-weights; he is confined to the scale case. He has no time for observing the test-piece, besides that his point of observation, especially in case of horizontal machines, is always inconveniently located. The machine is provided (*623–635*, Pl. 18) with holders which exert lateral pressure (serrated wedges) and allow a certain amount of travel during the test. I was convinced by actual observation, however, that these holders do not always hold securely. The observer confined to the scale cannot always determine by behavior of the scale whether this is the case or not, and cannot see it in horizontal machines. If it is desirable to work with certainty and to watch the entire test, and to also make observations of deformation, it will be necessary to have two observers, especially in horizontal machines. This should be avoided in testing materials, and it is possible to do so if the hints given below are observed (see *559*). This objection here made to the Emery machine—not to be forgotten—is an objection which is valid for many other types of machines, as well as the Werder machine.

But the Emery machine in particular could easily be so constructed on a more skilful design that the observer might have the scale directly beside himself and in a most compact form. This design is not a matter of economy, but should above all things be preferred, because the observer should always be in a position to observe all occurrences personally and to take the responsibility of all detail throughout the entire test. This point of view cannot be neglected in future designs of testing-machines, if any claim for perfection be made. This seems to me to be of greater practical importance than excessive sensibility, or of an unnecessarily high degree of accuracy, which as a rule exist only in the imagination. If we were to subject our machines, in regard to the two last respects, to a careful and exhaustive, although very difficult, practical examination, and not only in the unloaded but also in the loaded condition, we should probably arrive at highly surprising results, and find that in most of our types of machines their degree of accuracy does not amount to as much as we sometimes imagine to be the case. I fear that it will be found by such an investigation that the Emery machine is no exception to the rule; it might, however, be found that the plate-fulcra do not prove their great superiority over knife-edges. The use of plate-fulcra for physical balances was tried by very able persons in Germany before Emery, but was again dropped. This appears to me to be proof that it was learned how much more could be achieved by knife-edges and how much more certain and reliable they are. I was fortified in this view by the fact that although I saw a great many Fairbanks scales and other types, I failed to notice

any Emery scales, nor did I see laboratories equipped with the Emery type of analytical balances. Sellers does not build Emery scales, and I did not receive definite answers when I referred to my observations. Whether I have overlooked the existenee of Emery scales, or whether they could not be introduced in a manner commensurate with the pompous advertisement which the system received, I cannot say.*

My observations of the operation of the scales used with the Emery machines, and of one of his large gauges, make it appear possible to me that the excessive sensitiveness and the ceaseless vibrations are caused by the great lever-ratios, and by the circumstance that the resilience of the many plate-fulcra make themselves too markedly felt at the instant of equilibrium.† The position of the ideal bending-points of the plate-fulcra must be affected by the position of the levers; the bending-points of the fulcra of each lever do not lie in one plane. Without an exhaustive study it is difficult to determine to what extent this produces errors of weighing. The levers would hardly have been made so massive without good reason, for the inertia is always noticeable, even when the motion is very slight. Hence the question arises, to what degree the masses, the elastic deformations of levers, of the movable connections, and also of the fulcra, act upon the accuracy and sensitiveness, as is known to be the case in our ordinary beam-scales..

It is self-evident that elastic deformations and thermal changes are not without effect on the Emery machine, and therefore it is a question whether the gain due to rigidity of beam obtained by increase of mass is not more than counterbalanced by the greater difficulty of thermal adjustment and increased load of the machine frame.

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* Prof. Martens failed to find even a single example of an Emery grocer's or analytical balance, not because the system was unsatisfactory, but simply and solely because financial reasons prohibited their manufacture and the commercial development of their introduction.

† I cannot agree with Prof. Martens in these statements. My varied experience with the weighing scale of the Emery testing-machine demonstrated that these vibrations of the pointer ceased almost instantly when the correct balance was established. In fact, in no machine did I ever notice such immediate quiescence of the system, and it was always the failure to properly balance the load which caused vibrations. This became most noticeable by balancing the scale under a steady load and then adding to or removing small loads from it; the pointer would assume a corresponding position with a promptness that I never observed in any other machine, although I have examined several for this very quickness of response.

Prof. Martens' statement about the Emery gauges is correct, because these are not balanced by weights as in the scale, but by a spiral spring which vibrates considerably before coming to rest.—G. C. Hg.

My prejudice—which I at present admit—against the superiority of plate-fulcra is also caused by the fact that there is but a single method of determining the exact lever-ratios of the Emery scale, actual weighing, which, however, is also the ultimate method in knife-edge scales. The measurement of lengths seems unreliable, because it is not known to what extent initial stresses in the plate-fulcra, produced by their forcible insertion in the grooves in the levers, affect the position of the ideal axes of rotation. As far as I am concerned the question remains: is the plate-fulcrum balance in fact more certain and perfect than that having knife-edges? An exhaustive investigation can alone be decisive; and it is desirable that this be done at the proper place.

The reader will observe that my criticism of the Emery machine is essentially directed against the construction of the scale. The determination of ratios of hydraulic chambers and the scale of the Emery machine can of course only be done empirically on the finished system of chambers. At Sellers' shops, I saw an admirable arrangement for this purpose, and I was convinced that they work in a most conscientious manner, and that only superlatively perfect work is done there. But it must not be forgotten that one is very largely dependent upon the original calibration, especially in horizontal machines (which alone Sellers builds); for the auxiliary means for calibrating completed testing-machines are at the present day still very awkward and incomplete. Great honor would be due to him who would devise a simple reliable apparatus for rapid calibration of testing-machines under full loads.

505. The action of knife-edges during transmission of force may be considered, as Schwedler casually remarked, "as floating" of the material of the knife-edge on the material of the seat. The two bodies will undergo elastic deformations until they have sunk into each other sufficiently to produce equilibrium. The knife-edge must be regarded as a perfect cylinder of very small diameter and the seat as one of very large diameter. Load always produces surface-contact, and this may, if desirable, be regarded as a transition into the condition of the plate-fulcrum. For the elastic knife-edge rolls on the equally elastic seat when the lever oscillates, and a shifting of the line of contact must take place, although it be very minute. We are dealing to a certain extent with a very short and very thin plate-fulcrum having a width equal to the effective length of the knife-edge.

506. Therefore, as slight indentation and change of surfaces of contact always exist in actual knife-edges, the question was asked by several constructors whether it would not be proper, in case of levers with very slight motion, to use knife-edges with measurable rounding in place of the minute flattening of the edge. Accordingly, Pfaff (Pl. 13, Figs 15–17) designed the main knife-edges with cylindrical surfaces. I cannot state from personal experience whether this produces any material practical diminution of the accuracy and sensitiveness of the testing-machine, as I have not had occasion to examine such a machine. The use of cylindrical knife-edges certainly has the advantage of reducing their unit stress very materially, hence also of effectively diminishing permanent deformation and wear; under heavy loads the knife-edges may be made shorter, hence more resistant against bending-stress.

When considering all of these conditions, it must be borne in mind that it is amply sufficient if testing-machines have **a reliable accuracy of 1% for indicating loads.**

Greater accuracy is difficult to attain, and also unnecessary, because materials themselves possess a considerably greater degree of variability (*L 102, 128*).

4. Lever-scale with loose weights.

507. The lever-scale with loose weights, and scale-pan in simplest form is found in but few machines, e.g. the Werder machine, Pl. 3, Figs. 1–3. This arrangement generally requires an assistant additionally to the observer, who in the Werder machine also operates the valves and pumps. Testing-machines should, however, be so designed that the observer can operate the machine singly during tests, besides making all observations, assuming the entire responsibility therefor.

508. Lever-scales having levers of constant length and weights deposited mechanically

are used by Emery (*502*), Fig. 355; Gollner, Pl. 13, Figs. 1 and 3, Nos. 47–56; Martens, Pl. 5, Figs. 1 and 3–5, Nos. 27–61, and Pl. 13, Figs. 18–31. In large machines of the last two types the weights are deposited by screw and hand-wheel; in my small 5-ton machine, Pl. 13, Figs. 23 and 24, by levers 33 and 34 and the angle-levers 21, which lower the supports for weights 18 or 25, thus depositing weight after weight. The number of weights deposited may be read on the ratchet-arcs 35, adjacent to the pawls of levers 33 and 34, so that the observer may read the load directly without leaving his place. Lever 33 operates the large weights for 1-ton (1000-kg) increments, and lever 34 the small weights 25 for 55-lb. (25-kg) increments. In my 50-ton (50,000-kg) machine, Pl. 5, the large and small weights are placed above each other. The small series of weights is deposited or removed by hand-wheel 38, Fig. 1, while the series of large weights are moved by the worm-gearing 43, Fig. 5. The small disks 30 are for 1-ton (1000-kg) and the large disks 31 for 10-ton (10,000-kg) increments. Gollner also uses a similar loading device for a series of weights, Pl. 13, Figs. 1 and 3, but on a different principle. While Emery and Martens use series of equal weights, Gollner uses four unequal weights, 47–50, Fig. 1, so that by means of a proper combination of these and a number of small weights not shown in the drawing and a sliding poise any desired load from 0 to 45,000 lbs. (20,000 kg) may be balanced to 1.1 lbs. (0.5 kg). [These small increments can have but little practical value when it is considered that errors of 1% must be admissible in tests (*506*)]. Gollner's arrangement of weights requires the additional use of hands for depositing small weights, because wedges must be inserted by hand in the central suspension-rod 46. These wedges catch the weights which are to be used; thus the use of the four weights 47–50 can be varied at will in any desired combination.

509. Among scales of constant length of lever must be mentioned that of F. Michaelis, Fig. 357, a type of ma-

chine having a shot-feed. This machine is used mostly for tension-tests of cement and mortar briquettes; it has been adopted as the standard cement-tester in Prussia, and has also been very largely introduced outside of Germany. In this type the weights are all minute and uniform, equal to the total weight of all the grains of shot deposited. If water be used, Fig. 358, instead of shot, a uniform increment of load is obtained (*L 259*).

a. Because of the importance of the Michaelis machine in cement-testing, and as an example of various points which must be considered in testing materials, I shall here describe this apparatus more fully; its principle is shown in Fig. 357. The functions of the loading mechanism are assumed by the scale; although a hand-wheel *h* with screw is provided, this is only used for initial adjustment. The scale has a leverage of $\frac{1}{50}$ and is designed for 1100 lbs. (500 kg). The load *p* is a lot of lead shot, which flows from the vessel *S* by a spout the orifice of which can be so adjusted that a definite quantity, about 0.22 lbs. (100 gr) can pass per second. When the test-piece is ruptured, the bucket *p* drops and strikes the locking-lever *N*, which arrests any further flow of shot. The weight of the bucket and shot is then hung from the eye *o* and weighed by the lever H_1 and some small weights placed on the pan.

In spite of this construction, which must seem at least awkward to the engineer and mechanic, and in spite of the awkward manipulation, the Michaelis machine has been very largely used. This is certainly due to the ready comprehensibility and accessibility of the individual parts, ease with which it can be checked, and also as a cause of the shape of test-piece used and the good holders. But the fact that it was adopted as the official apparatus in Prussia probably assisted in its general introduction. It is remarkable how many imitations and improvements were made of this apparatus. Special attempts were made to improve the shot-feed, whose de-

fects and inconvenience were apparent to all, by substituting water: compare Reid's apparatus (*L 47*, 1878), Fig. 358. Generally the quantity of water was indicated on a gauge-glass conveniently expressed as tenacity in lbs. per sq. in. (kg/sq. cm). How much safer and simpler would the pendulum-balance be for this purpose!

b. The scale has been calibrated by the Charlottenburg Testing Laboratory, by direct loading up to its capacity (500 kg), as to accuracy and sensitiveness, and was also tested for deformation of details, and stood the test satisfactorily (*L 1*, 1896, p. 177). It was found that the lever-ratio of the apparatus tested changed but very slightly; it was found to be an average of 49.93 instead of 50.

An addition of .002 lbs. (1 gr) deflects the beam $\frac{1}{2}$ in. (12 mm) from the horizontal, while 0.2 lbs. (10 gr) depresses it 2 in. (50 mm) as the deflection may amount to about 1.2 in (30 mm) at instant of rupture, the load for this reason is noted as $7.5 = 0.77$ lbs. (350 gr) less than the correct amount; i.e., the tenacity of the standard briquette of section $a = .077$ sq. in. would be too low by $S_M = \frac{0.77}{0.77} = 1$ lb. $\left(\frac{0.35}{5} = 0.07 \text{ at.}\right)$. Hence the error in tenacity, taking the standard of 28-day briquettes at 227.5 lbs. per sq. in. would be $-$ 0.44%.

c. The speed at which the shot falls into the bucket is also of material importance; for this reason the Prussian standards prescribe .22 lbs. (100 gr) per second. The orifice is to be regulated accordingly. The size of shot and the condition of surface also exert an influence upon flow of shot. In course of time this changes for the same orifice, because the surface of the shot is affected not only by the air, but also by accidental jamming between orifice-slide and the trough. This may produce more or less interruption to flow. The following results of tests show the great effect which these conditions may exert.

d. Tests of the flow made with the same apparatus gave the following results (h = height of rise of slide for opening trough; p = weight of shot in oz. discharged per second):

1. **Shot 0.1209 in.** (3.1 mm) **diam.**

   a) old, frequently used:

   $h = 0.433$; 0.468; 0.581 in.

   $p = 3.1$; 4.31; 8.38 oz./sec.

   b) new.

   $h = 0.405$; 0.433; 0.468; 0.581 in.

   $p = 4.93$; 6.19; 7.99; 14.43 oz./sec.

2. **Shot 0.058 in.—0.097 in.** (1.5—2.5 mm) **diam.**

   $h = 0.378$; 0.405; 0.433; 0.468

   $p = 3.03$; 4.24; 5.20; 6.49 oz./sec.

Frequent interruptions to flow occurred in 1 *a*); when $h =$ 0.433 in. flow often ceased after 8–9 sec.; the shot flowed smoothly in 1 *b*). This shows how carefully the apparatus must be handled if unobjectionable results are to be obtained.

e. A certain time elapses between instant of rupture and cessation of flow of shot. The result will be too great by the amount of shot which flows after the instant of rupture. The drop of the bucket is about 2 in.; hence the time elapsing before the orifice is closed will be $t = \sqrt{\frac{2h}{g}} = 0.1$ sec. Under normal flow the quantity which runs out in $\frac{1}{10}$ sec. is therefore about .02 lbs. (10 gr), or about 1.1 lbs. load on the briquete. The tenacity would hence be too great by about 1.4 lbs. per sq. in.; this would be 0.5% in excess of the 28-day standard of tenacity. The effect of the impact of the shot on the bucket is, however, indeterminate.

f. The shape and suspension of the holders for the tension-briquette is shown in Fig. 359. The stirrup is supported on a pivot and therefore adjusts itself readily. The

;ripping surfaces of the stirrups should be slightly rounded as hown in sections *a–b*, in order that the briquette be held at four oints which are as near as possible to its centre plane. Oblique gripping, and production of bending-stress in the ma-erial, are nevertheless not excluded. In order to determine he possible error practically, several series of tests were made, vith intentionally exaggerated oblique grips; the mean error n each case was:

a	*b*	*c*	
21.5 (22.6 at.)	328.5 (23.1 at.)	334.2 (23.5 at.)	lbs. per sq. in.

An essential error was not proven, which is particularly hown by the values given in the original report; the limits of rrors of test are too large in themselves.

510. Buoyancy of water (hydrostatic balance) has lso been used in the design of a scale with constant lever-arm nd uniform increase of load; see Petit's machine (*L 102*, 888, p. 41, Fig. 28; *L 39*, 1885, p. 646), Pl. 15, Fig. 25. The nonstrosities thus produced are readily shown by the dimen-ions of the float, which is about 59 in. diam. by 54½ in. (1.25 × 1.38 m). It is to be noted that thermal expansion of water nd of the vessels must affect the load for ⅜ in. rise of scale. The other details of the machine are shown by the drawing.

5. Sliding-poise Scale.

Poise-weight and Scale.

511. The sliding-poise scale is very largely used in test-ng-machines. It no doubt offers some advantages and is apable of further improvement.

In the simple sliding-poise scale, the poise sliding on the eam, or on a special bar parallel thereto, is either moved by and or set at special marks or notches, which correspond to efinite multiples of the weight. The poise-weight and beam-ength are not always so designed that the entire capac-

ity of machine can be followed by the poise to the end of the beam; frequently large increments of load are balanced by independent weights attached to the end of the beam, the intermediate loads being balanced by again sliding the poise over the beam, which is again returned to 0 for each additional weight added.

Sliding-poises of the first type are often arranged for use of several weights, so that either a lighter or heavier weight is used, according to requirements. The distance travelled by the poise is hence increased for light loads, and small moments can then be read with greater certainty. The same scale is then generally used with weights of ratios 1 : 10 : 100 or of 1 : 2 : 5 : 20 : 50, so that the moments can easily be read on the same figures of the scale. Frequently two or more poises of different weights are used side by side, which then have ratios of 1 : 10; 1 : 100; or 1 : 1000. Then the large weight is advanced notch by notch, and the small weight travels over the length of beam, to indicate the intermediate moments.

512. The use of large poises or weights may be considered as an increase of scale, i.e., an increase of lever, which is equal according to the above ratios to the two-, five-, or ten-fold length of the actual lever. The readings will be smaller and may be accurate if the graduation of scale is accurate, when the lever-ratio remains constant while loading, and if the sensitiveness of the scale suffices for the fine readings. In view of the apparent exaggeration of lever-ratios in some testing-machines, the question should be asked whether such extreme lengthening is necessary and serviceable? I believe I should answer this question negatively.

As we must be convinced that irregularity of material hinders us in general to determine its resistance within an accuracy of 1% (neglecting very exceptional cases, this limit in the

greater number of cases not even being reached approximately), and knowing that it is exceedingly difficult to insure a degree of accuracy of testing-machines materially greater than 1%, and also that our most perfect measuring instruments for determining deformation do not insure greater accuracy than 0.5%; when we, as practical designers, also know that the average values used as bases of our calculations do not correctly represent the true properties of materials; when, furthermore, we know that our calculations are only approximations, which certainly deviate from the actual truth by more than 1%, what is the sense of exaggerating the accuracy of scale-readings? Why do we not remain within the limits of practical necessity and of that which is attainable by simple means?

I am of the opinion that if scale-levers be made of sufficient length so that loads producing rupture of the smallest test-pieces for which the particular machine may reasonably be expected to be used can be determined within 1%, this should suffice; for just as absurd as it would be to measure seconds by a Black Forest Clock (wooden mechanism), just so absurd would it be to test wire, or even horsehair, on a 100,000-lb. machine.

With a limit of necessary accuracy of 1% it would suffice if the beam were divided to $\frac{1}{1000}$ of the capacity of the machine. If the divisions be sharply cut and the spaces be about 0.04 in. (1 mm) or more, it would still be possible to estimate $\frac{1}{5}$ or $\frac{1}{10}$ of the divisions, hence $\frac{1}{5000}$ or $\frac{1}{10000}$ of the maximum capacity, or 10 lbs. on a 100,000-lb. machine; the error inherent in a single reading need not be assumed to exceed ± 20 lbs. Most likely the machine will be far less accurate. Sensitiveness sometimes even exceeds this; my 50-ton machine (Pl. 5), for instance, when unloaded, indicates 1 lb., which is hung on the jaws. If the scale be sufficiently sensitive it will still be possible to measure increments of about 2,200 lbs.

(1000 kg) with a single poise-weight with sufficient accuracy for measurements of precision, for the mean error of beam would be far less than 1%, as series of and not individual values are always determined in such case. If it is desirable to balance the beam with still greater accuracy, provided its degree of sensitiveness is sufficient, it should be so arranged that a second lighter poise ($\frac{1}{10}$ of the larger poise) can be used when it is desired to make measurements of precision.

513. I should here like to revert to a proposition previously made (*40*). By skilful design of the poise it would be easily possible to adjust it in every case proportional to the section of test-piece *a*, in tension-test, so that the readings of the scale would indicate directly stress *S* per sq. in. of the test-piece. A few principal poise-weights would be provided for usual sections, and so arranged that they could be connected with the actual sliding-poise, so that shifting of centre of gravity is impossible For larger variations from standard sections due to errors of workmanship, and which are not negligible, auxiliary adjusting weights would be required. In connection with such an arrangement deformation of the bar could be read off directly in per cent of original length in accordance with the directions stated in (*40*), (*137*), or recorded by the machine, and results of tests thus obtained which would be directly comparable with each other, or would coincide if the material be identical. The great advantages to be obtained thereby are explained in (*40*); they shall not be here repeated, but it will merely be pointed out in how many ways the desired end may be attained.

514. As well as using a constant scale with a poise of variable value, a constant weight and fixed leverage can be used with scales varying in proportion to the cross-sectional area, so that the corre-

sponding stress may be read off on the proper scale. It is not necessary to cut a number of scales on the beam for this purpose. A proportional scale with dividing lines radiating from one point may be attached to the beam. This rule would then answer for all scales applicable to any value of sectional area lying between a certain minimum and maximum, and but a single indicator on the poise would suffice, which, as shown in Fig. 361, would at every instant indicate the stress for any particular section. The indicator would of course be so arranged that it could be made to run accurately on any line representing a definite section. If the expedient be used of employing several poise-weights, the proportional scale would not be a very formidable affair. The proportional scales might also be mounted on metal strips, interchangeable on the beam. They could also be wrapped around a cylindrical drum, so that the line corresponding to a definite section may be revolved directly under the pointer of the poise by turning the cylinder. These scales could also be mounted on the frame of the machine parallel to the beam if the poise-weight were suitably designed.

Motion of the Poise.

515. The most various devices for moving the poise are in use, and hence I shall describe only typical designs. Adjustment by hand in its simplest form has already been described. This motion is frequently transmitted by a special device operated by hand, by a string or screw to the poise-weight, by which it is attempted to keep the beam floating constantly. The string or screw drive must of course be so designed that the force applied to move the poise will not produce a moment acting upon the beam. The direction of force and of resistance must pass always through the knife-edge.

516. The string drive of the poise-weight is used in

the Delaloë machine, Pl. 15, Figs. 19 and 20 (*L 38*, 1887, p. 273; *L 34*, 1891, p. 25), and in the Greenwood & Batley machines, Pl. 17, Figs. 1–6.

517. In the Mohr & Federhaff machine, Pl. 6, Fig. 1, the screw 26, supported at both ends on the beam, is driven by a parallel shaft mounted on the frame, and a set of gearing which makes contact in the prolongation of the supporting knife-edge of the poise-lever. The torsional moment of the gearing acts normally to the plane of oscillation of the lever, so that the very slight friction between teeth alone may exert very little effect upon the sensitiveness of the scale. The driving-spindle can be operated by hand-wheel at either end.

518. The Grafenstaden machine, Pl. 8, Figs. 1, 2, and 30, is provided with a similar arrangement. The worm-wheel 40 drives the screw 8 which operates the poise-weight 9. The lever-scale reads to 40 tons (40,000 kg); if the machine is to be used up to 50 tons, the auxiliary weight corresponding to 10 tons is attached, and its value added to the readings. The worm-wheel 40 and worm 8 make like revolutions to those of driving-shaft 39 with hand-wheel 37. The scale-beam has divisions of 500 kgs. One revolution of the hand-wheel 37 moves the poise one division, and as the hand-wheel is divided into 50 parts, each division represents 10 kgs. The revolutions of this wheel are indicated by a graduated disk revolving horizontally, divided into 500 kgs; the position of the poise on the beam can be read on it.

518a. L. Paupier, Paris (*L* 183, p. 12, Pl. I, Fig. 27), builds cement testing-machines operated by the travelling poise-beam. These machines are designed for tension- and crushing-tests up to 4400 lbs. (2000 kg).

519. In the Wicksteed machine, Pl. 16, the heavy poise is carried by wheels rolling on rails on lever 13, and is driven either by hand and hand-wheel 17 or by belt drive 23. Forward and backward motion is controlled by handle-bar 41. Motion is produced by gearing 16 driving the screw 15. In

the latest type of Wicksteed machine the poise is driven by an hydraulic press (*L 235*).

520. The travelling poise of the Martens torsion machine, Fig. 350, takes the shape of a roller 7, which revolves on centres in the counterbalanced fork of a carriage which moves on guide-rails and is driven by a screw. The position of the carriage and hence of the roller are read off on a scale and hand-wheel (524).

521. The Wicksteed machine has already been mentioned (*519*) as an example of a mechanically driven poise. In this machine the operator must also, however, regulate the speed of poise in such manner that the beam remains continuously floating in equilibrium as nearly as possible. In other machines the design is such that the machine itself controls the speed. This auto-regulation may be provided in several ways. Generally the loads are applied at a uniform rate, and then varying the moment of the load.indicator in such manner that the beam remains almost constantly at 0. The reverse method can, however, be adapted by increasing the moment of the load-indicator at a uniform rate, and then regulating the application of load in such manner that the beam remains floating at 0. The motion of the beam is generally used to regulate that of the driving mechanism in the first case.

522. During my visit to the United States (1893) I saw an arrangement * in which the poise-weight was operated by simple mechanical means, controlled by the beam. I show the scheme of this machine, from memory, in Fig. 362, as I unfortunately lost a part of my notes while travelling. The device had been added to an old machine. The poise *p* was moved on the beam by a weight 5 driving the mechanism 1. The nose 2 on the beam arrested the motion of mechanism 1 when descending; hence it would operate only

* The C. H. Morgan, Worcester, Mass., machine is of this type.— G. C. Hg.

under increase of load. A roller 3 is shown on the poise, carrying a driving-connector, attached at 4 to the frame of the machine. The construction was actually much simpler; I desire, however, to call attention to the fact that the direction of moving force must pass through the main fulcrum, and, above all, to produce an intermediate type, leading to that shown in Fig. 363, which shows how this simple device may be designed to drive the poise forward and back. Two driving-ratchets, 1 and 4, operated by weights 5 and 7, shown in Fig. 263, are provided, which are alternately released by pawls 2 at end of beam when the latter oscillates. 4 controls the return, and 1 the advance of the poise. Weight 6 merely tightens the string.*

523. The principle just described is actually also that underlying the diagramming apparatus which I constructed for my 50,000-kg (50-ton) machine, although the moving poise of the scale is replaced by a rising and falling mercury-chamber of a gauge. The principle may also be used for the operation of a beam-scale in the form adopted by me. My apparatus is fully described in (*L 162*), in which I have published the numerous results of tests obtained therewith when attempting to produce very great multiplying ratios. Because this example is particularly instructive, I have described it in (*563*), although it is only of secondary importance in testing materials; I therefore limit myself at this time to the statement that it consists of duplicate electrically controlled operating devices, which carry the mercury-chamber (poise) suspended from a loose pulley. The left-hand device is driven by a heavy weight and raises the chamber, while that at the right hand is operated by the descending chamber and a smaller weight. The operation of one or other of these devices is interrupted by an electric current, which is controlled, independently of the force transmitted to the test-piece, by an

* In the Morgan machine weight 6 is replaced by a spring within 3.—G. C. Hg.

electric contact, in such manner that the apparatus invariably oscillates with minute play about the position of equilibrium of the straining device. The mercury-chamber thus follows the load on the test-piece accurately, and its position is a measure of this force.

524. The apparatus might also have been controlled by water instead of electricity, as in the previous case.

I took advantage of the Berlin Accident Prevention Exhibition to illustrate this principle on a small 1000-lb. machine, which was built to my plans in the Laboratory shops and which was a laboratory exhibit. It is shown in Fig. 364, 1/12.5 nat. size.

It is driven by city water acting on the packed plunger 3, which moves in either direction controlled by cock 22. The poise is carried by a carriage 9 on centres in a fork oscillating about the middle fulcrum, so that the weight of the large roller almost alone bears on the lever. The carriage runs on the lateral rails 8; it is driven by a clock-spring 10, attached to the post 11 fixed to the carriage. The beam 7 can oscillate but slightly between adjustable screws 23. This play is transmitted to rod 18, which operates a balanced slide-valve in the chamber 19. The passages in chamber 19 are milled, as shown in Fig. 364. Very sharp closing is thus secured, and a slight play of $\frac{1}{100}$ inch (a few tenths of a millimeter) suffice for reversing. This connects the upper and lower parts of cylinder 20 alternately with the pressure and with the exhaust-pipe. Thereby the clock-spring 12 attached to connecting-rod 21 is moved forward and back, which sets 13 in motion. The latter must follow the motion of the reversing-valve, i.e. of the beam 7, and thus the poise is kept moving by the clock-spring 10 attached to 13, keeping the beam floating about the position of equilibrium. The position of equilibrium is, however, dependent upon the stress in the test-piece. The reciprocating motion of the mechanism is transmitted by a rack to the plate 14 rolling on the guide 15. The pencil also records

elongations of the test-piece, being coupled to the lower jaws 5 by means of the rod 16 and clamp 17.

525. The driving mechanism of the Olsen machine, Pl. 20, and the operation of the poise are shown by Fig. 365. I shall here describe the entire mechanism, which is used slightly modified, in all Olsen machines. Comparison of Pl. 20 with Fig. 365 will facilitate the comprehension thereof.

In the Olsen machine the poise is operated by the driving mechanism by means of a wrapping connector operating a screw; the direction of motion is controlled automatically by the oscillations of the beam acting upon an electric controller. The main driving-spindle operates the wrapping connector, and is itself revolved in either direction by an open and a crossed belt and pulleys 1 and 2, Fig. 365, accordingly as the friction-couplings gear right or left. This motion is transmitted by a gear-train 4 to 11 to the four screws of the cross-head 31 (12 are four ball-bearings, reducing friction). The tension-stress is thus transmitted indirectly to the test-piece and the cross-head 30, or directly through the crushing test-piece to the platen (omitted in the figure) supported by the forked levers at ab. These levers transmit loads to the intermediate levers a_1b_1 acting on the weighing-beam a_2b_2. The screw operating the poise-weight is carried by the weighing-beam, on the left end of which a graduated disk is mounted which has two friction-wheels, acted upon by the small wheel 19, revolving the disk 20 to the left or right according to which edge it is in contact with. This floating driving mechanism is reversed in either direction by the electromagnets, 21 and 22 by the current from the battery 26, when the contact 25 is closed, increasing the load, and decreasing it when contact 23 is closed. If the poise cannot keep pace with increment of load, the spring contact 25 is closed and then 24; this operates the bell 27, which attracts the operator's attention to the existing conditions. The operator can then increase the speed of poise

by adjusting the conical belt speed-regulator 18. This is driven by belting 13 to 17 as the screw 28 forces the friction-wheel 14 carried by the lever against 13. The graduated disk 20 shows 100 and tens, while the 1000 lbs. are indicated by the position of the poise on the beam-scale.

526. The driving mechanism of the Riehlé machine resembles the Olsen in its entire design; its scheme, omitting several intermediate gears, is shown by Fig. 366. It is driven by straight and crossed belt; the clutches 3, 10, 13 and friction-wheels 5, 6 and the gears 4, 7, 8, 9, 11, 12, 14 to 20 operate the straining-screws 21 at different speeds. The screws 21 transmit forces to the tension or crushing test-piece, whence they pass, either directly or indirectly, first to the table (omitted in Fig. 366) and through it to the four supporting points of the two forked levers ab. Lever a_1b_1 transmits the load to the scale-beam a_2b_2. The poise is operated by the band 31. This belt is driven from the main spindle by pulleys 25 and 26, the latter of which may be coupled to disk-wheel 29 by the electromagnetic clutch 27, 28. 29 drives the friction-wheel 30, which can be adjusted across the face of 29 by hand, and thus operates the belt 31 in either direction and at any speed. The contacts at 32 control the operation of 28.

527. The travelling poise itself is peculiar; it carries a revolving graduated disc by which 100's and 10's are read off through an opening, while 1000's are read off on the beam. The disk is revolved by a rack on the beam.

528. Riehlé also uses a scale-beam with travelling-poise in which the beam itself carries a screw, while the revolving nut within the poise-weight is driven by a light spindle on the lever and a crown wheel. The nut is thus moved automatically with the poise, which runs on wheels rolling in a groove in the screw. The scale-beam is divided into 1000 lbs., and the nut into 100's and 10's.

529. The design used by Fairbanks is much more complicated. The poise is moved by electromotors contained

530. When using mechanical or electrical controllers for the poise the foregoing will show that two methods of operation, which, however, merge into each other, are possible. In the one (Fig. 368 is an exaggerated case of it) the control of the poise is arranged in such manner that the beam may play and come to rest between its two extreme positions (between contacts), while in the other the device is so adjusted that reversal of motion is so quickly repeated that the poise-weight vibrates about the position of equilibrium even under a steadily increasing load. This can be done in several ways. I used two methods in my 50- and ½-ton (Plates 5 and 524, Fig. 364) machines.

(*a*) Although the travel of poise about the position of equilibrium in this ½-ton machine represented a variation of load of 33 lbs. (15 kg), it was nevertheless possible to notice a variation due to 4½ lbs. load in the diagram recorded (see 2–6, Fig. 369), a part of which is shown in Fig. 369, thus making it possible to determine loads to about 1½ lbs. (1 kg).

(*b*) In case of the motion of the mercury-chamber for the 50-ton machine I went still further (*563*).

In this case the reversal of the two controllers was so rapid that the brake-levers were constantly buzzing. Therefore the pencil, operated by the constantly rising and falling mercury-chamber, drew a line on which serrations were no longer visible. This was achieved by the use of a contact, in the circuit of which an accurately adjusted relay controlling the currents of the brake-levers was inserted. Each make and each break produced reversal, and the speed with which this was done was as nicely adjustable as above stated. Although I devoted much study to and obtained very good results with this device [as will be seen from the instructive report (*L 162*)], it also finally succumbed to the fate which is the end of all such complicated arrangements; it is no longer used because simpler devices have been substituted.

b. The Pendulum-balance.

531. The principle of the pendulum-balance underlies many load-indicators of testing-machines in a more or less striking manner. It is found in its complete form in the Pohlmeyer, Schopper, v. Tarnogroki, Michele, and in others of all modifications, which merge appar-

ently into the ordinary lever-balance. While in the pendulum-balance the changed position of lever is used as a measure of all applications of load, the possible motion of beams between stop and position of equilibrium is rarely ever used in beam-scales for that purpose. The beam-scale acts as a pendulum-balance when the variation of position of beam is used to balance small loads instead of balancing the beam by shifting the poise. Attention may here be called to the fact that they may be considered as pendulum-balances even when no apparent use is made of this method. Every scale-beam bends; hence motion must take place about the middle knife-edge during increasing stress on test-piece even when the beam bears on the stop because of overweight of poise. It would in fact be possible to use this distortion as a measure of transmitted load by means of proper measuring-instruments (mirror apparatus or levels) if the end fulcra were fixed to the machine-frame. In this case we would be dealing to a certain extent with a pendulum-balance in which the pendulum-ball did not change its position, but its size increased constantly to an amount necessary to produce the distortion of the beam. It may suffice to have called attention to this point; true pendulum-balances alone shall be here discussed.

532. The theory of the pendulum-balance of the Pohlmeyer machine has already been given in (*65, d*). Referring to the schematic illustration Fig. 370, I wish to discuss some peculiarities, while the construction itself is shown on Pl. 9, Figs. 1–18; the same notation is used in both cases. The machine is driven by hydraulic pressure, and its speed is controlled by the valve shown in Fig. 339. The power is transmitted through the table and the rods 6 to the upper cross-head and the test-piece, thence to the lower cross-head and the rods 11 to the main lever 15 of the scale. It is transmitted by means of 17, 19, 20 to the pendulum 21 of the balance, the motion of which measured by the rise of rod 40 is transmitted by a string to the pointer 25. This rise, and hence the travel of pointer,

is, according to (*65, d*), proportional to force P in the test-piece, and hence by changing the distance m the scale of readings may be changed, or, what amounts to the same thing, a given uniform scale may be used to indicate stress if it be mounted at a corresponding distance m from the centre of rotation of the pendulum. By simply moving the support 23 with relation to axis of pendulum the load-indicator may be adjusted if the investigation of the machine proves the existence of errors.

It is clear how very readily the Pohlmeyer machine may be made to comply with the requirements in (*40*), as it would merely be necessary to move the support 23 along a scale, divided according to sectional areas of test-pieces, to read off stress directly. One graduated circle would then answer to read off all stress in at. for all sections used.

533. The reading and recording device designed by me for the Pohlmeyer machine and built by the laboratory mechanic E. Boehme, Charlottenburg, is shown on Pl. 9, Figs. 19 to 27. It corresponds with the foregoing descriptions, and would also answer for recording diagrams of stress if the arrangement just described for moving support 23 were provided. Hence it would be merely necessary to measure records of extension by a scale divided according to % of the gauge-length, or to select such value for l_t that a millimeter scale could be used directly to read off % of l_t or elongation e% (*38–40*). I arranged the load-indicator * shown on Pl. 9, Figs. 19–27, in the following manner. The main bar 40, guided at top by three rollers 58 and at the bottom by rollers 41, runs on one roller on the upper surface of the pendulum-lever 21 (Fig. 2); hence the bar retains its distance m during the test.

* Bach (*L 27*, 1890, p. 1042) used an apparatus designed on similar principles and constructed by G. Boley in Esslingen, to indicate deformations of flat plates tested by hydraulic pressure.

At the top of 40 a water-proof silk trout line passes around a sheave 56 and is strained by a spring 57, and wound about the spindle of the indicator in two loops, transmits the motion of the bar to it. This spindle runs on points, in front in a recess in the knob 54, and in the back in a nicely adjustable bearing in the cross 48, so that the indicator is visible throughout its complete revolution, the front mirror-plate being the support. The graduated circle 55 for indicators 51 and 52 is carried by a ring in the case 47. The spindle carries a counter-disk 49 by means of a stop, and load of 10 tons may be read off through a slot. The indicator makes five revolutions for the capacity of the machine, which with a diam. of nearly 8 in. (191 mm) equals a straight scale about 10 ft. (3 m), or 2.4 in. per ton (60 mm) in the 50-ton machine, and 1.2 in. (30 mm) per ton for the 100-ton machine. In the first case the graduations read to 0.02 tons, in the second case to 0.05 tons. Tenths thereof may still be estimated.

Adjustment of the indicator to 0 is effected by shortening or lengthening the rod by means of screw 42. To avoid injury to the apparatus at the instant of rupture and the drop of pendulum, I recently designed an eccentric clamp, which was, however, replaced by the builder in a very practical manner by the ratchet shown in Fig. 24. Two collars 45 are provided on rod 40, and carry a sliding bolt 44; it drops by its own weight. When rising (loading the machine) the pawl will engage the ratchet carried by the frame of machine, but on account of the possible motion of the bolt will permit descent of bar 40, and also of the indicator 51, until the bolt strikes the upper collar 45. Hence the rod and indicator may respond to the drop of load at yield-point and during stricture, but are arrested by the ratchet from striking the pendulum-lever at rupture. The indicator 51 carries a loose pointer 52, nicely mounted on the knob 54, by which it can be adjusted to 0. The stop is so arranged that the indicator is only carried forward and hence remains in position of maximum load.

534. So as not to repeat, I shall in this place describe the recording-apparatus designed by me. The rod 40 carries the pencil 65 mounted on two pivots and pressed against the drum 60 by a reversible spring. The paper is secured on the drum 60 in a very simple manner after lapping the ends by the spring 61, which fits behind a screw at the lower end and a clamp at the upper. The drum revolves very freely on two pivots in the frame 59. It is revolved proportionately to change of length of test-piece by a string passing around single or compound sheaves. The diameter of sheave is selected according to the multiplication of elongation with which it is recorded. The transmission of extension is usually done by means of a few rollers led vertically from the cross-head of the machine. This therefore records the relative motion of cross-heads. This is of course admissible only when the diagram is used as a picture or control for direct measurements; this is the rule at the Charlottenburg Laboratory. The motion of the drum should in other cases be derived from the test-piece itself. In order occasionally to use the apparatus for more accurate work, the string-guiding device shown in Fig. 371 is used. It is connected to the frame by the stirrup 1, and consists of two adjustable tubes 2 and 9, which are connected by pivot-screws with each other, the stirrup and the test-piece (or the cross-head). Rollers 4 and 7 for the string 14 are secured in the frame in such manner that the centres of motion of individual links lie in the effective roller surfaces; therefore no motions of levers 2 and 9 of any kind can produce motion of string. Hence the motion of string is produced only by change of shape of test-piece between gauge-marks when the pivoted screws of the elastic and interchangeable stirrup 13 are set in the gauge-marks, and when the other end of the string 14 is secured to the other gauge-marks by spring-clamps. To avoid changes of length of the braided silk line it is waxed (to exclude effect of moisture) and heavily loaded for some time before use (diminution

of permanent extension and secondary effects). When in the machine, it is always kept strained by a balance-weight. The variations of stress in the string are hence caused only by friction and inertia, which must be small, as all parts run on pivots. The string 14 is secured to the second gauge-mark by the bent steel spring 2, Fig. 372, one end of which has a small loop 5 to which the string is tied. To insure safe attachment of the springs 2 at the gauge-marks, their ends are flattened as shown at 3 and 4 and hardened, one of which is cut off square as at 3 for rounds, and pointed for flats, while the other, 4, has a knife-edge angle. This invariably insures a safe, unconstrained bearing on the bar, particularly because the moment of weight of spring due to shape selected is very small (in vertical position) and equal to 0 because supported (when horizontal).

a. It will be instructive, and again lead to the conviction of the necessity of accurate examination and constant calibration of testing-machines, if I here present a small part of the very exhaustive investigations of the Pohlmeyer machines made at the Charlottenburg Laboratory. I can only present incomplete results, because even the great Charlottenburg Laboratory lacks means and assistance to carry out these very valuable examinations in an entirely methodical manner, and to extend them beyond the limit of absolute necessity, or even to properly digest the valuable information obtained. I hope that these communications will lead to a more general consideration of the question of calibration of testing-machines, so frequently mentioned by me, than has heretofore been the case. I especially hope to induce builders of testing-machines carefully to consider the points raised by me.

b. The many investigations of the Pohlmeyer machine at once led to the abolishment of a series of irregularities, which at my suggestion its builder has since avoided in all machines. Formerly the lever-fulcra were not secured against longitudinal shifting. This produced a constant change of sensitiveness of machine. This defect was remedied by introducing guides as shown in Figs. 9–14, Pl. 9; since then the machine works splendidly. In the 50-ton (50,000-kg) machine other changes have been made. At first I had the two counterweights 14, Figs 2 and 3, which easily caused oblique action in rods 11, replaced by a single lever, as in Fig. 373, which acts in the line of stress of the machine at the lower cross-head. As this cross-head always has a motion of several millimeters on a radius of 7.2 in. (180 mm) about the axis of the main lever, it is fun-

damentally wrong to attach the counterweighted lever, swinging in an opposite sense, rigidly to the cross-head without an intermediate movable link. I therefore made the balance-lever 2 first act upon an intermediate oscillating strut 4, and then upon the cross-head. I wish to state that this is by no means a satisfactory solution, because unstable support is secured, but the piping already provided did not permit of a better solution, by means of suspension-rods, without serious disturbance. Lever 14 also balances the weight of lever 15, Fig. 2, Pl. 9, at the same time, and causes this lever, even when unloaded, to bear upon its rigid support.

c. It is especially difficult to prevent the test-piece when under crushing-stress from exerting great lateral stresses before rupture. These are transferred to the rods 11 in the type now built and shown on Pl. 9, and produce bending-stress in the cylindrical casting 2 when the rods bear against the guides. In the machines of the Charlottenburg Laboratory, this bearing is produced only by great lateral thrust (wood cubes, etc.,) because the guides of the machine were bored out (about $\frac{1}{8}$ in.), immediately the machine was put into service, to obtain ample clearance, and to be able to observe this condition readily by the position of rods 11 in their guide-holes. This of course insures a greater certainty of results of tests, because unnoticed frictional resistance cannot easily creep in; nevertheless it is very inconvenient for fine work to work with the limber rods. This induced me to provide the guides as shown in Fig. 374, which absorb the lateral forces and convert them into frictional resistance, after overcoming the slight play. But these are very slight, especially in tension-test, and need hardly be considered in ordinary tests. As these changes had just been completed, an exhaustive examination, which was also to include the measurement of frictional resistance in the case in which the direction of stress does not coincide with the axis of the machine by 0.4 in. (10 mm), could not be made; a case which certainly will never again occur in this machine.

d. In order to obtain a preliminary knowledge of the resistances to motion, I made a crushing-test without great care in centring the test-piece, and applied a load of at first 10 tons and then 20 tons. To find the sensitiveness of the entire machine, a rider of 44 lbs. (20 kg) was placed on lever 14 and alternately removed, then taking readings on the load-indicator. The effect of change of load necessarily passed through the entire system. As I intended, if possible, to determine frictional resistances as well, I took double readings, one after raising the lever above the position of equilibrium by hand and then allowing it to settle very slowly (A), and again after depressing the lever slightly and allowing it to rise very gradually (N) to its position of equilibrium.

It was not possible, however, to obtain permanent equilibrium, because of existing leaks, and nothing remained but to take readings under gradually falling pressure or decreasing loads. I present the

record, to show how results may be obtained even under such conditions, when observations are made at regular intervals, arranging them to proceed at uniform speed.

Table 30. **Calibration of Machine N for Sensitiveness.**

A = lifted and slowly settled back, N = depressed and allowed to rise slowly.

Load and t	Readings 1 division = 2 kg				Readings 1 divison = 1 kg		Remarks.
	Loads on lever.				Loads on lever.		
	0 kg		20 kg		0 kg	20 kg	
	A_0	N_0	A_{20}	N_{20}			
10	25	21	42	38			* Considerable lifting A and also depression N (see Fig. 375).
	17	12	32	30			
	7	4	25	22			
	2	−3	17	14			
	−9	−13	8	5			
	−15	−18	2	0			
20	52	45	61	56	420	450	
	24	20	38	33	405	430	
	4	2	14	10	385	412	
	*) 100	95	114	111	368	403	
	85	79	98	96			

The readings (division on load-indicator) of the first column of Table 30 have been plotted in Fig. 375 as ordinates, the test numbers as abscissæ. It will be seen that we succeeded to a certain extent to take reading at uniform intervals of time. Hence parallel lines of average values may be passed through these series of values, and the distance between them, measured on the ordinate, is a measure of the effect of adding 20 kg on the lever when under a total load of 10 tons or 20 tons. According to Fig. 375 this effect under the loads stated:

$$10{,}000 \text{ kg } \Delta a = 40 \text{ kg}$$

$$20{,}000 \text{ kg } \Delta a = \begin{cases} 44 \text{ kg} \\ 43 \text{ kg} \end{cases}$$

A similar analysis of col. 2 Table 30, produces the following result:

$$20{,}000 \text{ kg } \Delta a = 38 \text{ kg.}$$

This is a very close approximation of values found under very different conditions of loading.

The great sensitiveness of the machine will be easily seen from the lines in Fig. 375; it will be noticed that the observed values (dotted lines) almost coincide with the full lines (averages).

[illegible] the follow-[illegible] series [illegible] position of [illegible]

[illegible]

[illegible]	[illegible]		[illegible]		[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$\Delta_2 - N_2$
	[illegible] = [illegible] kg.		[illegible] = [illegible] kg.			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2
	[illegible]	[illegible]	[illegible]	[illegible]	4	4
	[illegible]	[illegible]	[illegible]	[illegible]	4	3
	[illegible]	[illegible]	[illegible]	[illegible]	4	3
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8

[illegible] the machine

$$[illegible] = 5.6 \pm 3.96 \text{ kg.}$$

[illegible] error of adjustment $= \pm 2.46$ kg.

To further prove the accuracy with which the machine will assume the position of equilibrium after allowing the pendulum to swing freely, I made the following series of tests:

Readings: 709, 709, 707, 707, 707, 707, 706, 706.

In this case the pendulum was drawn out of its position by about 2 tons and released; it made a double vibration in 2.2 sec. and came to rest after 2.5 min. at the readings given above; load 700 kg. These series show the excellent sensitiveness, and prove that the addition of the guides will hardly have great effect in tension-tests.

e. As shown on Pl. 9, Figs 23 and 25, the pointer of the load indicator carries a roller bearing on the surface of the pendulum-lever 21, Fig. 2. The theory of the pendulum-balance developed in paragraph 65, *d*, presupposes that the end of the rod (as correctly constructed by P o h l m e y e r) travels on a plane passing through the axis of the pendulum. I made the roller of 2 in. diam. so as to have minimum friction, but thereby introduced errors, as shown by Fig. 370.

The indication will be too large, because of the finite value of r, by the amount J, calculated from the constants of the apparatus, as and

r, and from the true displacement n of the pendulum for a given force P:

$$\Delta = r\frac{1}{\cos\alpha} - r = r\left(\frac{1}{\cos\alpha} - 1\right).$$

Table 32 gives the errors Δ for $r = 25$ mm (1 in.) for different angles α, and in

Machine $N =$ 50 tons; $m = 344$ mm (13.54 in.)
" $O =$ 100 tons; $m = 520$ mm (40 4 in.)

as values of n, Fig. 376, for the angles α. Hence the last two columns give the errors in % of values of n.

Table 32. Erroneous Readings of Machines N and O for $r = 25$ mm (1 in.)

α°	2	4	6	8	10	12	14	16	18
$25\left(\frac{1}{\cos\alpha} - 1\right) = \Delta$ mm	0.015	0.061	0.138	0.246	0.386	0.558	0.765	1.008	1.287
n mm $= m \tan\alpha$ N	12.01	24.06	36.16	48.35	60.66	73.12	85.77	98.64	111.17
n mm $= m \tan\alpha$ O	18.16	36.36	54.65	73.08	91.69	110.50	129.65	.....	......
Δ in % of n N	0.13	0.25	0.38	0.51	0.64	0.76	0.89	1.02	1.16
Δ in % of n O	0.08	0.17	0.25	0.34	0.42	0.51	0.59	....	....
Δ in kg N	6	25	58	102	161	272	318	420	539
Δ in kg O	11	46	104	186	293	422	580	....	....

The actual loads would be less than the readings by the above values.

These errors may be avoided if the bearing surface of the roller be lowered by an amount sufficient to bring the axis of roller in the planes of the original rolling surface of the pendulum-lever. This produces the same effect as making $r = 0$. This has been done in both machines at the Charlottenburg Laboratory. It may be remarked that the error might also be reduced by shifting the support slightly, i.e. by changing m, if the support be adjusted in such manner that correct readings be obtained at the centre of the scale. This condition was always obtained, as shown in *f*, before the machines had been changed. Hence the actual errors of the machine are now much smaller than those calculated in Table 32.

f. The machines at the Charlottenburg Laboratory are regularly tested for accuracy by so-called standard bars. I made the following report (*L 222*) thereof:

"The testing-machines at the Charlottenburg Laboratory, and others upon order, are calibrated by means of a number of standard bars, which for years have been used for regular calibration of machines and apparatus in the following manner."

"Several standard bars are regularly tested up to 10 tons load on the 50-ton machine of my design, Pl. 5, which is invariably calibrated for lever-ratios before and after this test, by actual loads hanging freely therefrom. All standard bars (even those mentioned later on) are made of different carefully selected materials, and always strained only within the elastic limit. By means of mirror apparatus of my design (*88* and *692–699*) it was determined by a large series of tests that each bar shows the same extension for each 1 ton of load up to 10 tons. The extension produced by 1 ton of actual load is calculated from the lever-ratios determined by actual weights both before and after test."

"The many series of tests made in the course of years demonstrated that the standard bars only suffered practically immaterial changes. The total extension of the standard bars may be determined to an accuracy of 3 units of measurement (0.0001 mm = 0.0000039 in.); there is great certainty in measurements of extension, as the errors, with some care and the invariable use of the same instruments, may easily be limited to a few tenths of a per cent."

"The other machines of the laboratory are then tested to 10 tons by means of the three (or more) standard bars tested up to 10 tons. If each machine gives the same results with each bar as was obtained in the 50-ton machine, it may be assumed with great probability of certainty that it is correct up to 10 tons load."

"The variations of readings from the standard readings give the error of lever-ratios; they are corrected by adjustment when greater than 1%, or are recorded and applied as corrections when necessary, if less than 1%."

"As the lever-ratios may change with increased loads (in many machines there are various reasons for regular variations), it is necessary to calibrate a machine up to its maximum capacity. For this purpose the laboratory has several standard bars, which can be subjected to 100 tons safe loads within the elastic limit, the material of which has been carefully studied in small test-pieces in the 50-ton machine as to its proportional limit. These bars of 2¾ in. (70 mm) diameter may be used in four machines in the laboratory. If the extensions of these large standard bars for each 10-ton interval of load on a machine just previously calibrated by the smaller standard bars be found to be identical up to 100 tons load, it may be assumed with a great probability of certainty that the lever-ratio of the large machine has not changed during loading to 100 tons, and that these bars comply with the law of proportionality, because several bars of different material behave alike. These bars may then be used for calibrating other machines, the lever-ratios of which may be ascertained on the basis of extensions, or which may be adjusted until the readings of extensions correspond with the standard readings. This system of calibration has been extended in the laboratory to the 500-ton machine, the standard bar for which is 6.3 in. (160 mm) diameter and 29.5 ft. (9 m) long."

"Mirror apparatus used in this method of calibration, as long as the same instrument is invariably used under identical conditions, is really nothing but a very delicate indicator, and does not serve actually as instruments for the determination of absolute values of extension. The calibration is based on the assumption, which may at present be considered practically safe, that the bars do not change."

"The possibility of such change is not precluded, but we may be pretty independent of the effect thereof by using several bars, and subjecting them and the machines to simultaneous repeated calibration; it is improbable that several bars change in the same manner at the same time."

"It seems to me that the method pursued by the Laboratory is at present the only feasible one to obtain reliable calibration of our own and foreign machines. But the difficulties of such calibration are very great, and thanks would be due to him who would find a safe and quicker method."

"I may add that the method will be improved at the Laboratory by the addition of apparatus which will permit of loading the standard bars by 10 weights of 1 ton each. This device will then be used for the direct comparison of mirror apparatus, and a double calibration of the latter will thus be secured."

"In addition to those obtained from the machines at the Testing Laboratory, the calibration of other machines has enabled it to gather very extensive experimental data."

g. The calibration of the machine N, after being changed as explained in *e*, making the rolling surface so that $r = 0$, gave the results as shown in Table 33 and Fig. 377.

Fig. 377 gives the diagrams of mean values of extensions in 0.00001 cm in Table 33, obtained from different bars for intervals of loads of 0.5, 1.0 or 5 tons. The figures and curves show that the first load always produces greater values than the following. Hence an initial resistance must exist, deducible from the series of numbers in lines 3, 7 and 14, under the supposition that the extensions for other intervals of load may be considered identical for loads up to 10 tons. This would mean that extensions in bars k and c can be calculated from equation

$$e = e_1 + \beta n,$$

in which n = reading of load-indicator. Hence for

3. $e_1 = 122.9 - 113.9 = 9.0$; or $\frac{9.0}{113.9} \cdot 500 = 40$ kg (10 series).

4. $e_1 = 238.7 - 228.5 = 10.2$; or $\frac{10.2}{228.5} \cdot 1000 = 45$ kg (24 series).

5. $e_1 = 150.61 - 145.82 = 4.79$; or $\frac{4.79}{145.82} \cdot 1000 = 33$ kg (25 series).

e_1 on an average corresponds to an initial load of 38 kg.

Table 33. Calibration of Machine N by Standard Bars.

All measurements have been made by mirror apparatus *Bc* 15 and 16; in individual series, the averages of which are given, the bar was usually entirely released, turned or removed and the instruments readjusted. (For exceptions see below.)

(Compare Fig. 377.)

Marks on Bars.	Date of Test.	Number of Individual Series.	Extensions in 0.00001 cm on 15 or 20 cm gauge-length for Loads.										Average.
			0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
k 1	18–20 I 97	6	124.0	113.7	114.3	114.7	113.3	114.0	114.0	114.3	114.3	113.	
2	15–18 III "	4	121.3	113.3	113.5	113.5	115.5	114.3	114.0	113.3	113.6	115.0	
3	Average 1 and 2	10	122.9	113.5	140.0	114.2	114.2	114.1	114.0	113.0	114.0	114.	(113.0)
4	From Series 3	10	—	236.4	—	228.2	—	228.3	—	227.0	—	228.3	
5	25 VI 97	1	—	—	—	227.3	—	227.8	—	227.8		228.8	
6	24–29 VII 97	13	—	240.5	—	220.7	—	228.4	-	229.4		228.9	
7	Average 4–7	24	—	238.7	—	229.0	...	228.3		227.4	—	228.6	228.3
			1	2	3	4	5	6	7	8	9	10	Average.
c 8	21 I 97	3	152.0	143.7	145.3	144.7	145.0	143.7	144.3	145.0	141.1	143.7	
9	19 III "	2	154.0	146.0	145.0	144.5	145.5	147.0	146.5	147.0	143.8	147.0	
10	26 VI "	3	—	143.3	144.7	144.3	146.0	145.3	145.1	145.0	146.0	145.3	
11	12 X "	*) 5	150.2	145.4	145.0	147.0	145.4	145.8	145.0	145.6	145.0	145.4	
12	12 X "	7	151.1	145.7	145.6	146.3	146.3	144.7	146.0	145.9	145.1	145.4	
13	14 X "	5	148.2	146.6	145.2	146.4	146.2	145.8	146.0	145.6	144.8	145.4	
14	Average 8–14	25	150.61	145.32	145.21	145.88	145.86	145.89	145.60	145.66	144.08	146.07	145.86
7 15	18–25 VI 97	5	—	134.8	132.4	134.0	133.8	133.8	133.8	130.8	138.0	133.8	133.8
			0.1	1.5	10	15	20	25	30	35	40	45	Average.
V 16	29 VI 97	4	—	101.5	197.8	198.3	196.9	196.9	195.5	196.0	194.1	193.8	
17	30 VII "	4	26.0	104.1	197.5	197.8	117.0	197.0	195.0	195.5	193.0	194.0	
18	Average 16–17	8		102.9	197.7	198.1	196.7	196.8	195.1	195.8	194.7	194.9	196.1
VI 19	28 VI 97	3	—	102.1	197.0	198.7	196.0	196.0	195.5	196.0	194.1	195.8	196.0

* Series 12–14: bar and apparatus unchanged; rods supported by levers at 12, suspended at 13 from wire, at 14 from rod

In order to prove that the initial resistance, producing e_1, existed at the very beginning the following series of measurements under load intervals of 0.1 and 0.01 tons were made:

Table 84.

Series.	0.0—0.1	0.1—0.2	0.2—0.3	0.3—0.4	0.4—0.5		Average.
a	51	22	23	22	23	—	
b	36	25	23	23	23	—	
Average	43.5	23.5	23.0	22.5	23.0	—	22.0
	0.00—0.01	0.01—0.02	0.02—0.03	0.3—0.4	0.04—0.05	0.05—0.06	
c	20	6	—	6	—	10	3.7

Hence we have for series:

$$ab,\ e_1 = 43.5 - 23.0 = 20.5, \text{ or } \frac{20.5}{23.0} \cdot 100 = 89 \text{ kg.}$$

$$c,\ e_1 = 20.0 - 3.7 = 16.3, \text{ or } \frac{16.3}{3.7} \cdot 10 = 44 \text{ kg.}$$

These values varied considerably in individual series, and an average value of 70 kg had been deduced from series of previous years.

A definite cause for the extension e_1 has not yet been determined; it is certainly true that the frictional resistances are much smaller than 70 kg, for many direct determinations prove this. The different changes of the machine have not had any effect on this value.

Examination of the curves in Fig. 377 with bars V and VI under full load of the machine show a diminution of extension for intervals of increasing load. If the series of differences were averaged by a straight line as drawn, the general equation would require an additional term depending upon n^2 in the form

$$e = e_1 + \beta n - \gamma n^2.$$

h. The theory of the pendulum-scale as exemplified in the Pohlmeyer machine supposes, besides $r = 0$, that the force be applied to the pendulum in such manner that the direction of P remain parallel throughout the entire motion of the pendulum. Practically this cannot be so; greatest compliance will be obtained if rod 20, Pl. 9, Fig. 2, be made very long. If this is not the case, the load-indication cannot quite agree with the theory in (*65, d*).

Starting with the assumptions indicated by Fig. *378*, *a* (equilibrium $= \overline{1\text{-}1}$, motion $= \overline{2\text{-}2}$) we shall have for scale placed at distance $= m$ and play of pendulum n under angle α:

$$\text{tang } \alpha = n/m \text{ and } \alpha = \ldots\ldots;$$

[illegible] lever-arm a'_1 will be, if the direction of [illegible] as required by the theory:

$$a'_1 = a \cos \alpha,$$

[illegible] short arm of the pendulum.

[illegible] has a length $= b$, and assuming that [illegible] end of lever 19 be replaced by the [illegible] small motion, the ends will describe the paths 1 [illegible] $= 1$. The rod b will assume the position P', [illegible] by the theory. Hence the force P no [illegible] but the smaller, a_1. If β be the angle of [illegible] position from 1 to 2, we shall have:

$$[illegible] \left(\frac{a - a\cos\alpha}{b}\right) \text{ and } \beta = \ldots\ldots;$$

[illegible]

$$a_2 = a \cos (\alpha - \beta).$$

[illegible] machine (machine N of the Laboratory [illegible]), $m = 13.54$ in., $a = 4$ in. and b [illegible]

$$[illegible] = 0.34884;\ \alpha = 19^\circ\ 13'\ 50''$$

$$a_1 = [illegible] \cos 19^\circ\ 13'\ 50'' = 3.7173 \text{ in.}$$

$$[illegible] = 0.02232;\ \beta = 1^\circ\ 16'\ 44''$$

$$\alpha - \beta = 20^\circ\ 30'\ 34''$$

$$a_2 = [illegible] \cos 20^\circ\ 30'\ 34'' = 3.6874 \text{ in.}$$

$$[illegible]\ a_1 - a_2 = 0.0299 \text{ in.}$$

$$\frac{a_1}{a_2} = [illegible] = 0.8\%.$$

The force P must be increased by this amount if it acts in the [illegible] instead of P_1.

[illegible] details differ slightly from those here assumed [illegible]. These examples may suffice if it be stated [illegible] design the errors may be reduced even for initial [illegible] and rod b. The designer as well as the owner [illegible], however, have to contend with the initial errors of erection [illegible] the machine, and with the circumstance that all details and [illegible] elastic deformation, which must be considered in [illegible]. The position of the supporting surface of the pendulum also affords convenient means (534 e) to eliminate the errors of the entire lever system. This adjustment could moreover be made by actual trial by raising or lowering the bearing surface,

thus making the effective radius r of the roller positive or negative. This method will be pursued at the Laboratory to a certain extent to adjust the Pohlmeyer machines, which are for many reasons very convenient, to the greatest nicety. At present approximate adjustment is attained by shifting the block 23 in accordance with results from standard bars, and final corrections are applied when great accuracy is required. Practically it suffices to adjust the block by results with standard bars so that distance m gives correct results at 20 tons load; this reduces, as explained, the effective error, which remains below 1% of the indication.

k. The transmission of pendulum motion by means of the double trout line is slightly defective in spite of its certainty. This error is produced by the variable length of string because of its travelling in a spiral line. If the variable length in extreme position of string be 20 mm, thickness of string = 0.5 mm, diam. of roller = 7 mm, then, according to Fig. 378*b*, we shall have for 5 revolutions of roller a maximum error:

$$\Delta = \sqrt{(0.5 \cdot 2.5)^2 + 20^2} - 20 = 0.036 \text{ mm} = 0.0014 \text{ in.},$$

or expressed in revolutions of roller:

$$\Delta = \frac{0.036}{21.99} = 0.0016.$$

Hence the error of reading in most unfavorable position would not amount to 0.2%.

l. The errors previously discussed partly balance each other. Intelligent manipulation will certainly produce a very considerable diminution of errors; this is done to a great extent if the machine be calibrated by a standard bar, following the suggestions made in *i*. Nevertheless it is quite generally advisable to make sure by direct calibration from time to time that their accuracy is unchangeable, or to determine their degrees of error.* It is not strictly admissible or necessary to consider a machine as accurate if this accuracy has not been determined by unobjectionable calibration-tests. The numerous calibrations made by the Charlottenburg Testing Laboratory on its own and other machines have amply demonstrated that even in machines well constructed and finely maintained it is not very easy to keep their error below 1%, as required by the International Resolutions (*L 128*). Among foreign machines calibrated by the Laboratory some were found having errors of 16% (*L 223*).

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*So as not to be misunderstood, I wish to especially emphasize the point that this statement is quite generally applicable and does not refer alone to the Pohlmeyer machine, here used as an example.

535. The machines of Schopper, Michele and v. Tarnogroki are also based on the principle of the pendulum-balance. The scheme of the Michele machine is shown by Fig. 379 (*L 183*, p. 13, Pl. II, Fig. 8); it was built (in 1878?) for forces of 1000 and 1500 lbs. It is intended for tension-tests of cement, and should be very good for this purpose when well constructed. It is driven by a crank and worm-wheel which acts on the parallel-motion lever a_1. The other lever, a, is the short arm of the pendulum-balance, the long arm, b, of which carries the pawl s, indicating the load by the scale. In order that the weight p may not drop at instant of rupture the stop f is provided, which permits the holders to separate about 0.4 to 0.6 in. The principle can of course be used only on materials of slight extensibility, in which the true parallelism of motion cannot be materially disturbed. The error of the parallel motion detail becomes too great in very extensible materials, and the scale will no longer indicate the correct moment of force. The scale can then no longer remain uniform in the Michele machine, as is the case in the Pohlmeyer.

536. The Schopper machines, Pl. 11, Figs. 1–8, are especially intended for tension-tests under light loads, for thread, paper, cloth, wire, etc. Since 1890 they have been built of capacities of 10, 100, 500, 1000, and 1500 kgs (22, 220, 1100, 2200 and 3300 lbs.); these smaller machines have given great satisfaction in official tests of paper and cloth at the Charlottenburg Laboratory (*228*). Frequent calibrations of the machines invariably showed errors of less than 1%. The scheme of the machine is shown in Fig. 380. The axis of the pendulum 7 is supported on friction rollers. The short lever carries an arc which supports the holders 6 by means of a Gall chain; hence the length of short arm remains constant. The long lever carries the pendulum-weight, and an automatic pawl which engages a curved ratchet 2 attached to the frame of machine, thus arresting the pendu-

lum at the instant of rupture, and an indicator showing a maximum load on the graduated arc. The trailing indicator 13, mounted on the axis of the pendulum, indicates extensions on a scale 14 carried by the latter, and also remains in its maximum position at the instant of rupture. This is accomplished as follows: The lower holder is attached to a head which fits loosely on the driving-disk 5, being shifted axially by its own weight at rupture. This actuates the small angle-lever 9, its stop releasing the rack-bar 12, which until then transmitted the relative displacement of the two holders by means of the gear-wheel 13 to the strain-indicator. The machine is operated by gearing and a worm, which after rupture no longer affect the pendulum and strain-indicator, which record maximum load and strain. The latter is read in % of length, because identical lengths of test-pieces are invariably used. This is effected by running the train of gears backward, after having set the pendulum and upper holder at 0, until a stop on screw 5 strikes the lever 16, the end of which is depressed until it strikes a stop on the crank 3, thus locking the latter and preventing further motion. In this position of crank the distance between holders is exactly $= l$ (7 in. = 180 mm for paper strips). The holders are eccentric clamps, the construction of which is shown in Pl. 11, Figs. 5 and 6.

537. A. von Tarnogroki of Essen/Ruhr builds pendulum-scale machines in many sizes from 10 kg (22 lbs.) to 100,000 kg (100 tons).

W. Carrington of London, England, (*L 183*) (1878?) also builds paper-testers on the principle of the pendulum-balance.

c. Spring-balance.

538. The spring, in greatest variety of shape, has been used as an indicator of force since a remote day. Its application was, however, so awkward that the apparatus with spring-

balances have not been viewed with confidence. Defective action was, however, generally due to detail, and it may be asserted, on the basis of the ample experience obtained at the Charlottenburg Laboratory during more than 15 years, and with a large series of machines and measuring-springs, that the spring may be a very good instrument for measuring force if correctly used and calibrated, and if those limits of accuracy suffice which have heretofore (*505*) been demanded of testing-machines and considered ample.

As a matter of course I must confine myself to a selection, as the number of testing-machines with spring-indicators is very great.

539. The principal condition to be fulfilled in the use of springs is that the application of force and attachment of spring do not produce secondary stress; the spring should be able to assume changes of shape produced by stress freely and without constraint. For instance, a spiral spring will undergo correct extension, proportional to loads applied, only when the direction of force is axial without constraint during the entire test, and when individual rings do not touch each other. In closely coiled springs, as used in the Hartig-Reusch and the Wendler machines, to be described later on, extensions under tension can only become proportional to the loads, after the instant when all coils become free. Particular importance should be placed upon the connections with the machine details. In this respect I can agree with the constructions, as made in the Hartig-Reusch and Wendler machines, Pl. 11, Figs. 9–27. Hartig clamps the ends of the springs to the cross-bars by means of screws, and provides the cross-bars with eyes, by which and pins they are connected to the carriage 8 and the draw-bar 4, Figs. 9 and 10. Aside from the fact that it is almost impossible to make the points of application of

force exactly coincident with the axis of spring, the ends are not attached so rigidly that the springs cannot possibly slip in their clamps. If this occurs, the resistance of the springs must change, even though the actual spring does not undergo changes of properties of the material. By means of reference-marks, which indicate possible slip, we may have some check, but this is not a satisfactory condition. Wendler uses the same spring design, but he secures the ends of the spring by means of screws, riveting and soldering, instead of clamping, and then also files marks into the spring and the socket, to indicate any possible slip, which, however, has thus far not been observed to take place at Charlottenburg. The attachment of the Wendler spring to the machines is still more unfavorable than that of the Hartig; it will hardly remain without secondary effects on the spring in any case.

540. The Hartig spring connection, of course, permits adjustment of the spring to a definite scale, and readjustment of a spring to the same scale possibly altered by varying the length of wire (revolutions), but I should certainly prefer to work with a spring of rigidly determinate invariable length, and to calibrate the spring from time to time, determining its possible changes and making allowance for them, because every machine requires frequent calibration in all its parts, in any case.

541. In the Crosby indicator the question of spring-connection has been solved as shown in Fig. 381. The spring is duplex, and its upper ends are screwed several revolutions into a block having four vanes, to be able to adjust the spring to a definite scale. Although this connection is not without constraint, the many points of contest in the four vanes may produce the same condition as if the upper end of the spring were soldered or the block cast about it. If the block were adjusted in the cylinder in such manner that the sphere attached at the other end were made to move in the axis of the spring, which is readily done by turning off the upper end of the block after

attaching the spring, the latter must absorb the force of the piston connected to the sphere without constraint or flexure.

In every case in my designs where reliability was important I used open springs, and, where possible, connected directly to parts of the machines, without intermediate details, as is done in many spring-balances, etc. See Fig. 382.

542. The scheme of the Hartig-Reusch machine, Pl. 11, Figs. 9–13, is shown by Fig. 383. The test-piece is attached by one end to the machine (by means of the abutment 12, Figs. 9 and 10, adjustable to length of test-piece). The other end is attached to a carriage 8, which, running on rails, carries a pencil. A measuring-spring 7 is provided between the carriage and straining-mechanism, the extension of which as a measure of load is transmitted to the rack 14, which by means of the toothed sector 15 and rack 18 converts this motion into a vertical motion of the pencil, which therefore is a measure of force transmitted to the test-piece. The relative deformation of the bar is measured by the horizontal motion of the carriage 8, as the pencil records this motion on the card 20 attached to the frame of the machine. In order that the spring does not recoil at the instant of rupture and injure the apparatus, a pawl and ratchet 22 is provided, which prevents it. Power is applied by worm-gearing by hand or belt. Capacity is 44 lbs. (20 kg); readily interchangeable springs of 9, 20, and 44 lbs. capacity are used. The apparatus is built by Oskar Leuner, Dresden.

Because of its convenient form and simple design, and also the copious and valuable work of Hartig, and of his assistants and students (Hugo Fischer, Mueller, Connert and others), the machine has acquired a well-deserved reputation. It is particularly valuable for purposes of instruction, although it does not fulfil strict requirements. I prefer to use it for my students' work, because it admits of individual work more readily than larger machines, and makes it possible to enlarge the field of experiment without great loss of time and expense.

I determined its sources of error very carefully and exhaustively when it was to be used for official paper-tests at the Charlottenburg Laboratory. I shall merely refer to this pub-

lication (*L 227* and *215*), because it will suffice to discuss tests of springs, in connection with the Wendler machine, in the next section. A study of this report will again demonstrate the necessity of regular calibration of machines.

543. The Wendler machine is built especially for testing paper. It was created in the Charlottenburg Laboratory because of my advertisement in 1886 (*L 226*) for a special machine for testing paper; this suggestion also brought forth the Schopper machine (*536*). The Wendler machine is based on the principle of the Hartig-Reusch; it is shown by Fig. 384 and on Pl. 11, Figs. 24–27. The load is indicated by spring 11 with recoil-check 14, and it is driven by worm and gear. The extensions of spring 11 are transmitted to the indicator 19, indicating loads in kg on the scale 18. This indicator carries a scale at the other end, divided in % of gauge-length = 180 mm. The indicator attached to the other grip indicates the relative motion of both grips on this scale, hence the elongation of test-strip in % of l_g, of course under the assumption that there is no slip in the grips. The grips are eccentric cams, and slipping rarely takes place; lead-pencil marks drawn on the paper at the grips prove this.

The Wendler machines of the Laboratory are operated in groups of four by one small water-motor and belts. Each machine is provided with an automatic release designed by myself. The recoil-ratchet is attached to a lever, 21, which can move by a small amount. This motion is transmitted to the angle-lever stop 24, which releases the angle-lever 25, causing the driving-worm to drop out of gear; the machine stops and load and elongation may be read off on the scales. One observer can therefore operate four machines. Springs of 15 and 38 lbs. (7 and 18 kg) are provided.

a. The regular calibration of springs of the Hartig-Reusch machines used at the Charlottenburg Laboratory were described in 1887 (*L 215*, p. 36). I shall review these calibrations, prefacing them with the statement that the very frequent calibrations of the springs of the

Wendler machines which have replaced the former since that date have not shown any changes of any kind in these springs. The springs are as reliable at the present day, after many years' use, as at the beginning.

The springs are tested by means of carefully measured angle-levers attached to the machine-frame by special auxiliary devices, Pl. 11, Figs. 27 and 30. The same sealed weights are invariably used for loading. The load is brought to a balance by the machine, thus transmitting all of it to the spring. Relative extensions are either recorded on the paper, as in the Hartig-Reusch, or read off on the millimeter- or load-scale, as in the Wendler. The mean readings of five series of observations for identical increments are compared in successive tests with the scales provided, or used as data when constructing the spring-scales for new machines.

In the latter case extensions are first read off on the millimeter-scale. The series of differences for load increments are then calculated to determine those loads beyond which the springs extend proportionately to the loads. The readings are tabulated as in Table 35.

b. With this mean value of proportional extension $\Delta m =$ 7.593 mm for 0.5 kg load, a scale between limits 1 kg* to 6 kg is calculated, and opposite to it are placed the readings in Table 35, as has been done in Table 36 (again only for loads).

Table 36 contains the comparison of 5 defective scales, from which a satisfactory one is to be deduced. With this scale assumed to be correct, each of the erroneous scales can be compared. It would, however, be incorrect to adjust the one o to the other, because these also contain errors. Therefore the scales to be compared must be shifted in such manner that all divisions agree as nearly as possible, i.e., so that the errors still remaining become a minimum. This procedure can be applied

* I have here reprinted the tables in (*L 215*) in abbreviated form, as they are to serve merely as an example. For each individual case it must be decided whether the scale of spring is to be determined for the case of loading, generally sufficient, or also for the mean of loading and release.

to the five series of observations by considering each shifted with relation to the next by an amount equal to the means of Table 36, i.e., by deducting them from the observations. Thus the comparison given in Table 37 is obtained (again for loads only).

Table 35. Spring No. 1 for 6 kg Capacity.

Thickness of wire 4.4 mm; diam. of coil (unloaded) 86 mm. No. of revolutions 8.5.
Σ = extension; Δ = difference for each 0.5 kg; Δm = variation from mean value.

Loads kg.	Extensions in mm in Series. 1			2			3			4			5		
	Σ	Δ	Δm	Σ	Δ	Δm	Σ	Δ	Δm	Σ	Δ	Δm	Σ	Δ	Δm
0.0	0.0	—	—	0.0	—	—	0.0	—	—	0.0	—	—	0.0	—	—
0.5	—	—	—	6.3	6.3	—	6.1	6.1	—	6.5	6.5	—	6.2	6.2	—
1.0	13.2	(13.2)	—	13.6	7.3	—	13.2	7.1	—	13.6	7.1	—	13.4	7.2	—
1.5	—	—	—	20.9	3	−0.31	20.6	4	−0.22	20.9	3	−0.30	20.6	2	−0.41
2.0	28.3	(15.1)	—	28.6	7	+ 9	28.2	6	− 2	28.7	8	+20	28.4	8	+19
2.5	35.8	7.5	−0.13	36.2	6	− 1	36.0	8	+18	36.2	5	−10	35.9	5	−11
3.0	43.6	8	+17	43.8	6	− 1	43.6	6	− 2	43.9	7	+10	43.6	7	+ 9
3.5	51.4	8	+17	51.5	7	+ 9	51.3	7	+ 8	51.6	7	+10	51.3	7	+ 9
4.0	59.0	6	− 3	59.3	8	+19	58.9	6	− 2	59.2	6	0	58.9	6	− 1
4.5	66.5	5	−13	66.7	4	−21	66.4	5	−12	66.8	6	0	66.6	7	+ 9
5.0	73.8	3	−33	74.4	7	+ 9	74.0	6	− 2	74.4	6	0	74.2	6	− 1
5.5	81.7	9	+27	81.9	5	+11	81.7	7	+ 8	81.9	5	−10	81.8	6	− 1
6.0	89.3	6	− 3	89.7	8	−19	89.4	7	+ 8	89.6	7	+10	89.5	7	+ 9
Mean		7.63			7.61			7.62			7.60			7.61	

Grand average for load of all 5 series = 7.614 mm for 0.5 kg.

(N.B.—For loading and release the mean found was = 7.593 mm for each 0.5 kg, and with this value Table 35 was calculated.)

Table 36. Spring No. 1 for 6 kg.

Scale-point, kg	Scale deduced, mm	Readings in mm from Table 35. Load, Series. 1	2	3	4	5	Variations in mm from Scale deduced, Series. 1	2	3	4	5
1.0	0.0	13.2	13.6	13.2	13.6	13.4	13.20	13.60	13.20	13.60	13.40
1.5	7.59	—	20.9	20.6	20.9	20.6	—	31	01	.31	01
2.0	15.19	28.3	28.6	28.2	28.7	28.4	11	41	01	.51	21
2.5	22.78	35.8	36.2	36.0	36.2	35.9	02	42	22	.42	12
3.0	30.37	43.6	43.8	43.6	43.9	43.6	23	43	23	.53	23
3.5	37.97	51.4	51.5	51.3	51.6	51.3	43	53	33	.63	33
4.0	45.56	59.0	59.3	58.9	59.2	58.9	44	74	34	.64	34
4.5	53.15	66.5	66.7	66.4	66.8	66.6	35	55	25	.65	45
5.0	60.74	73.8	74.4	74.0	74.4	74.2	06	66	26	.66	46
5.5	68.34	81.7	81.9	81.7	81.9	81.8	36	56	36	.56	46
6.0	75.93	89.3	89.7	89.4	89.6	89.5	37	77	47	.67	57
		Mean					13.26	13.54	13.24	13.56	13.33

Table 87. **Spring No. 1 for 6 kg.**

Series	Loads in kg.												
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	−13.26	—	−0.06	—	15.04	22.54	30.34	38.14	45.74	53.24	60.54	68.44	76.04
2	— 54	−7.24	+ 6	7.36	06	66	26	96	76	16	86	36	16
3	— 24	— 14	— 4	36	96	76	36	06	66	16	76	46	16
4	— 56	— 06	+ 4	34	14	64	34	04	64	24	84	34	04
5	— 33	— 13	+ 7	27	07	57	27	97	57	27	87	47	17
Mean	−13.39	−7.14	+0.01	7.33	15.05	22.63	30.31	38.03	45.67	53.21	60.77	68.41	76.11
	As means of series for loading and release values below were found (*L 215*).												
Mean	−13.56	−7.18	−0.05	7.39	15.05	22.75	30.38	38.14	45.76	53.29	60.82	68.36	75.87

The most suitable scale for series 1–5 (loading and release) was deduced from last series in Table 37, by substituting for the mean value of zero of scale (for load = 0 kg). The differences between the last series, Table 37, and the scale constructed from the mean value 7.593 mm for 0.5 kg, Table 35, are found from Table 38.

Table 88. **Spring No. 1 for 6 kg.**

	Loads in kg.												
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
a) Mean readings.	0.00	6.38	13.50	20.95	28.61	36.31	43.94	51.70	59.32	66.85	74.38	81.92	89.43
b) Calculated scale	0.00	—	13.56	21.15	28.75	36.34	43.93	51.73	59.12	66.71	74.30	81.90	89.49
c) differences *a*–*b*			−0.06	−0.20	−0.14	−0.03	+0.01	+0.17	+0.20	+0.14	+0.08	+0.02	−0.06

c. In Table 39 a few values are given which were obtained in the regular calibration of the springs of the Wendler apparatus used at the Charlottenburg Laboratory to show to which degree they are reliable and how little they change.

It may be observed that, after spring 5 had been shown to have a wrong 0 by the first two calibrations, the scale was shifted accordingly. The mean errors thereafter are less than 0.2%. [Similar comparison of the calibration of Hartig-Reusch apparatus will be found in *L 215*, pp. 38 and 39.]

Table 89. Wendler's Machine No. 5.

a. Spring 9 kg.

Date of Test.	Error in % under loads kg												Remarks.
	0.0	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0	8.0	9.0	
24./4. 1888	—	+3.0	+2.0	+1.5	+1.2	+1.0	+0.8	+1.0	+0.7	+0.7	+0.4	+0.4	5 series of measurements.
13./7. 1888	—	+5.0	+3.3	+2.5	+2.0	+1.3	+1.3	+1.0	+1.0	+0.9	+0.8	+0.8	5 " " "
28./7. 1889	—	−2.0	−0.7	−0.5	−0.4	0.0	0.0	0.0	+0.2	+0.3	+0.4	+0.3	* 3 " " "
16./1. 1891	—	−1.0	0.0	0.0	−0.4	0.0	0.0	0.0	+0.2	+0.1	0.0	0.0	3 " " "
28./11. 1891	—	−1.0	0.0	0.0	−0.4	+0.3	−0.5	0.0	0.0	+0.1	0.0	0.0	1 " " "
13./9. 1892	—	0.0	0.0	0.0	0.0	0.0	+0.5	+0.4	+0.5	+0.1	+0.3	+0.2	1 " " "
14./9. 1893	—	0.0	0.0	0.0	0.0	+0.3	+0.5	+0.4	+0.2	+0.3	+0.3	+0.3	3 " " "
16./1. 1895	—	0.0	0.0	0.0	0.0	+0.3	+0.5	+0.2	0.0	+0.3	+0.3	+0.2	1 " " "
2./5. 1896	—	+1.0	0.0	0.0	−0.4	+0.3	+0.5	+0.2	0.0	+0.1	0.0	+0.2	1 " " "
19./10. 1897	—	+0.5	−0.3	−0.3	−0.4	0.0	+0.3	−0.2	0.0	+0.1	+0.1	+0.2	2 " " "
Mean.	—	−0.44	−0.13	−0.10	−0.25	+0.15	+0.23	+0.13	+0.16	+0.18	+0.18	+0.18	* Scale adjusted to correct 0.

b. Spring 20 kg.

Date of Test.	Error in % at loads kg																Re-marks.
	0.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	
24./4. 1888	—	0.0	0.0	0.0	0.0	0.0	+0.2	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	5 tests.
13./7. 1888	—	−0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+0.1	+0.1	+0.1	+0.1	+0.1	0.0	5 "
28./7. 1889	—	0.0	0.0	0.0	0.0	+0.1	+0.1	+0.2	+0.3	+0.1	+0.2	+0.3	+0.2	+0.2	+0.2	+0.2	3 "
16./1. 1891	—	−0.2	−0.1	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	0.0	0.0	−0.1	0.0	−0.1	−0.1	3 "
28./11. 1891	—	0.0	0.0	0.0	0.0	0.0	+0.2	+0.2	0.0	+0.1	0.0	0.0	+0.1	0.0	0.0	0.0	1 "
13./9. 1892	—	0.0	0.0	0.0	+0.2	+0.2	0.0	+0.2	0.0	+0.1	0.0	0.0	0.0	+0.1	0.0	0.0	1 "
14./9. 1893	—	0.0	0.0	0.0	+0.1	+0.1	+0.1	0.0	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	0.0	3 "
16./1. 1895	—	0.0	0.0	0.0	+0.2	+0.1	+0.1	0.0	+0.2	+0.1	0.0	+0.1	+0.2	+0.1	+0.2	+0.2	1 "
2./5. 1896	—	0.0	0.0	0.0	+0.1	+0.1	+0.1	+0.2	0.0	+0.1	0.0	+0.1	+0.2	0.0	+0.2	+0.2	1 "
19./10. 1897	—	0.0	0.0	0.0	+0.1	+0.2	+0.2	+0.2	+0.2	+0.1	+0.1	+0.2	+0.2	+0.2	+0.2	+0.2	2 "
Mean	—	−0.04	−0.01	−0.00	+0.07	+0.08	+0.10	+0.12	+0.10	+0.07	+0.07	+0.10	+0.10	+0.09	+0.10	+0.08	

544. Leuner's machine is also a modification of the Hartig, only the recording-device differs (*L 224*). While referring to the exhaustive description in the reference I wish to present its construction diagrammatically in Fig. 385. Loads are applied and force is measured as in the Hartig machine. The recording-drum 10 is mounted on a revolving axis 6 of a carriage moving on rollers attached to the frame. This carriage also carries a vertical axis 7, provided with bevel-gear and sheave 8. The band (steel) 9 is stretched across the frame 1. When the test-bar 2 extends, the bevel-gear 7 will cause the drum 10 to revolve. The extension of spring, measuring the force applied to test-piece, moves the pencil parallel to the axis of the drum, thus producing a diagram; 13 indicates a recoil-check.

545. Leuner also built such a machine, but with a hydraulic cylinder. This machine is described and illustrated in (*L 225*): it is here shown diagrammatically by Fig. 386.

The stress-strain diagram is recorded as before. The straining mechanism and load-indicator are modified. Loads are applied by means of screw-power 4 and hydraulic press 12, which forces the oil into cylinder 13. The piston directly connected to test-piece *z* contains a smaller cylinder 14, the piston of which actuates the measuring-spring 5 by the hydraulic pressure back of it, its extension being transferred to the pencil by means of 11. The recoil-device is replaced by check-valve 15. In this design the measuring-spring 5 receives but a small part of the total load in ratio of diameters of pistons 13 and 14. The machine is built up to a capacity of 2200 lbs. (1000 kg).

The Leuner machines require frequent calibration of machine and of springs, as will be seen from the design, because a rather complicated apparatus acts between the test-piece and load-indicator, the frictional resistances of which affect measurements. It will be necessary to secure accurate knowledge of sources of errors of all moving parts, as I did in the

Hartig-Reusch machine (*L* 227, 215). This is especially true of the hydraulic machine, in which piston and packing friction are present.

546. Instead of a spiral spring, any other spring having proportional deformations may be used. I made use of this principle in a small machine for tension-tests which I had constructed for the Charlottenburg Laboratory by our mechanic, E. Boehme, in 1885. The machine was a final link in a series of designs, which I used for the purpose of determining the effect of time on speed of extension and resistance of sheet zinc (*282–294*). I have reported upon the difficulties met with and the various tests made to achieve my purpose in great detail in (*L 115*). I here wish to repeat the following, taken from that report:

It was the problem to construct a load-indicator "which would produce release under a very slight extension of the test-piece. It is only possible to obtain this result by means of a spring of very slight extensibility, especially when it was to be the load-indicator and be connected directly with the test-piece. In the Hartig-Reusch, Wendler, and other machines having spiral springs of great extensibility, this favorable method of loading cannot be obtained, because the extension of spring sufficient to produce release is as a rule greater than the total expansion of the test-piece. As a result the material flows more rapidly before rupture, which is of great influence on results of tests, especially in soft materials, such as zinc.

"Springs of slight extensibility are obtained by using rods stressed to points within the proportional limit. Such a bar is placed between the test-piece and the abutment of the machine. As its total extension is but a fraction of a millimetre (parts of $\frac{1}{50}$ inch), it must be made manifest by magnification. This may be done in several ways, as by use of mirror apparatus and telescopic readings (*548*), by use of microscope, by use of mechanical multiplication, etc. (*547*). The attempt

to use the principle stated for purposes of recording diagrams was made, to my knowledge, simultaneously and independently by myself and by Kennedy (*L 182*); however, the idea is so simple and close at hand that it certainly has been considered and tried by others; among apparatus of this kind may be mentioned Fraenkel's Extensometer and Bauschinger's standard bar for the Werder machine [Leuner used this principle lately (*547, 548*)]. Kennedy recorded the extensions of the measuring-bar multiplied mechanically. I desisted from such a method on principle, because I dreaded the inertia of the moving masses, as well as all play and mechanical defects, which cannot be avoided in an apparatus as complicated and fine as is necessarily required for mechanical magnification. In order to touch only upon the essentials, attention must be called to the fact that in the motion of a pencil (even if it were a marking-point on lampblack, which leaves its trace upon a glass plate smoked with lampblack), the friction produced by writing must be overcome. If the apparatus writes on a magnified scale, the force necessary to overcome frictional resistance of the pencil is magnified likewise, and it is easy to reach a point at which marked errors are thus produced. Long levers necessary for great multiplication bend and give incorrect records; heavy levers call inertia into play. The points of application of forces at the short arms of levers can hardly be made otherwise than as pivots. These pivots will then be overloaded under great ratios, and play or backlash can hardly be prevented; at least it will be found to exist in a short time. These considerations have caused me to accept the drawbacks contained in the construction described below, and to desist entirely from a direct magnification of extensions of the spring."

The principle of my recorder is shown in Fig. 387 and in detail in Fig. 388. The numbers refer to the same parts in both. The machine is driven by a worm and gear 2, and loads measured by the steel bar 6. The bar 6 is forced at its right

end against the block 8 by means of wedges and rubber washers (not shown in Fig. 388), and attached by a ball-joint at the other end to a carriage 5 mounted on rollers, which carries the jaw 4 for holding the test-piece Z. The block 10 attached behind the carriage 5 serves to absorb the recoil at instant of rupture by its clamping bolts, and to keep it away from the steel bar. The guide 11 is pivoted to the steel bar 6 by means of two screws, so that it must travel with the bar when it is drawn away from 8 by increase of load. At the other end the guide 11 is lightly and movably supported on block 8, carried by two lateral supports 15 having hardened ends resting on bearing-blocks. The guide 11 is similarly guided in a horizontal plane by a guide and counter-spring 16. This method of guiding insures frictionless and accurate motion of 11 and enables it to respond to motions of bar 6 without restraint. It should, however, be observed that the slight motion on a circular arc of the end of vertical support 16 is a noticeably disturbing element in the diagrams, although the radius of the arc is 20 mm (0.8 in.) and the actual motion but 0.7 mm (.0273 in.); greater length of the support or use of a roller therefore seems advisable. This error has no effect on accuracy of load-measurements. The guide carries at its end a very neatly finished diamond-holder 12, held between hardened pivots and working without play. This holder has a counterpoise to accurately regulate the pressure of the diamond point on the glass. Besides this, the holder carries an adjustable rider for the purpose of shifting the centre of gravity of the diamond-holder over the supporting axis, and to cause the holder to tip by the recoil of rupture of test-piece, thus lifting the diamond from the glass plate. To prevent the recoil from causing it to again drop on the glass plate, it is caught by a spring on its first tilting, which hooks over the balance-weight screw. This detail should be very carefully adjusted to work properly, and is a difficult matter. The centre of gravity of the whole must in the first place be sufficiently high above the

axis of support, and secondly be sufficiently near to the diamond to insure tipping under recoil and also correct loading of the diamond. Furthermore, the motion of the holder necessary to cause the spring to catch must be small enough to cause locking even under slight recoil. This requires a weak spring, so as not to arrest the motion of the holder and thereby prevent locking. If the holder is not caught, the diamond point will, as a rule, strike the glass with sufficient force to destroy a material part of the diagram, even when the marks of the blow are not visible to the naked eye. The variable thickness of glass plates used is especially disturbing; uniform thickness must be maintained. The glass plates are of the size of the standard disks for microscopic preparations. They are secured to the carefully ground table 13 running on rollers. This table is moved by a micrometer-screw and counter-spring 14. In order to eliminate the errors produced by defective end surfaces from the action of the micrometer-screw, a short support with hardened points is inserted between the screw and table. The screw is carefully cut and without lost motion in the nut. The screw is driven either by hand or by a very fine watch-spring 20 by the extension of that part of test-piece from 17 to 17. For this purpose a silk string is repeatedly wrapped about a drum on the screw-spindle having a weight of 1 lb. at one end, the other being attached to the watch-spring just beyond the drum. The watch-spring is used to avoid the changes of length which cannot be avoided when using a string. As the test-piece was held by gripping wedges it became necessary to eliminate their slipping motion from the measurements of extension. This was done by using lever 18 with its two guide-rollers. One end of this lever is connected to the frame of the machine, permitting rotation, and the other abuts against a clamp 17 on the test-piece. The rollers are attached in such manner that the spring-tape passes around them, leads through the axis of motion of the lever, and also through the plane of the axis of the test-piece at 17, thence

leading to the other clamp 17. Both clamps are separated by a definite distance. This arrangement transmits only the relative motion of the two clamps to the carriage or slide 13, as all motion of the first clamp 17 merely produces motion of rotation of lever 18 about its suspension-point. The revolutions of screw 14 may be read off on a disk divided into 10 parts.

The diagram is produced on the glass plate by the motion of the diamond parallel to the spring 6, and a motion of the carriage normal thereto. As the diagrams are so small that two of them can be drawn within a space $\frac{1}{25}$ in. square, it is necessary either to enlarge them microscopically or photographically. Measurement by microscope, however, requires very sharp fine lines. This can be produced only by so-called ground diamonds properly weighted. The conical point is the most satisfactory, because it scribes with equal readiness in every direction; the angle of cone is from 60° to 90°. The laboratory mechanic has constructed the machine described in a very careful manner. The construction does not as yet, however, answer in all respects. The machine will be materially simplified and perfected by fixing the glass plate and transmitting motions in two directions to the diamond point in the manner shown by Fig. 389. The arrangement and support of guide 11 may remain the same as before in a vertical direction.

The clock-spring 20 should, however, be attached to the circumference of a large roller revolving on the same axis as a smaller one, by which the guide 11 is moved laterally by the spring 20. This motion is counteracted by a balance-weight.

The measurements of these diagrams were made by use of a large Zeiss microscope provided for this purpose with micrometers at objective and at eyepiece. The former measured extensions, the latter load ordinates. The objective *A* with same length of tube (sliding tube) was used for measurements.

Very exhaustive examinations of this apparatus have been made to determine its accuracy and are reported in (*L 115*, p. 12). It will here suffice to give the final results of values of loads

in Table 40. From these the greatest difference of 2.8 kg (6¼ lbs.) and average difference of about 1.5 kg (3⅓ lbs.) are found between the values calculated from the diagrams and actual loads.

Table 40.—Comparison of Final Results of Six Series of Measurements.

Load P kg	Difference ΔP kg	Values of $\Delta\gamma$ in R: Series 1	2	3	4	5	6	Mean of c–h	$1R = \frac{\Delta P}{\Delta\gamma}$ kg	Value of Scale-divisions. $\frac{\Sigma i}{R}$	Calculated $P =$ 48.05 R kg	Differences of Observations $a-m=$ kg
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*k*	*l*	*m*	*n*
Loads.												
0.00	—	—	—	—	—	—	—	—	—	0.000	0.00	0.00
84.19	84.19	1.948	1.783	1.713	1.628	1.630	1.583	1.714	49.12	1.714	82.36	+1.83
173.44	89.25	1.932	1.904	1.829	1.879	1.733	1.877	1.859	48.01	3.573	171.68	+1.76
265.42	91.98	2.032	1.896	1.916	1.997	1.907	1.888	1.939	47.44	5.512	264.85	+0.57
356.39	90.97	1.928	1.893	1.971	1.995	1.982	2.013	1.964	46.38	7.476	359.22	−2.83
448.62	92.23	1.955	1.952	1.947	1.727	1.984	1.908	1.912	48.24	9.388	451.09	−2.47
542.96	94.34	1.836	2.002	1.973	2.054	1.906	1.833	1.934	48.78	11.322	544.02	−1.06
635.96	93.00	1.843	1.938	1.930	1.934	1.988	1.898	1.922	48.39	13.244	636.38	−0.42
—	—	1.937	1.871	1.914	2.051	2.019	1.976	1.961	—	15.205	730.60	—
Mean	90.85	1.926	1.905	1.899	1.908	1.931	1.872	1.901	48.05			

The greatest variations between mean values and individual values are + 14 and — 10 in 48 observations. From this we see that the apparatus should be used only for tests in which such errors may be ignored, as is the case in tests of zinc, in which speed plays such an important part.

547. The Kennedy-Ashcroft apparatus (*L 182*, 1886, p. 63) is arranged as shown in Fig. 390. It is driven by worm-gearing 2–4 and loads indicated by standard bar 5. The recorder is attached to test-piece and standard bar, the card 15 of which is moved in the direction of the axis of the machine by the extension of the test-piece *s*, while the extension of the bar-spring 5 is recorded on a largely magnified scale by the pointer 18. The machine is designed in such manner that the record is free from all distortions and movements of all parts of the machine and of the bars beyond the marks 6, 7 and 16,

17. This is secured by use of the levers 10, 11. The well-conceived apparatus is supported from the two bars *z* and 5 without constraint. The connector 9 (steel band) is attached to point 9, and the upper arc on lever 10, while the lower arc on this lever is similarly connected by means of 13 to the card 15. The card 15 is drawn to the right by counterweight 14; it runs on guides on support 12, which latter is secured to point 19 midway between 16 and 17. At the other end 12 is suspended from lever 11, attached by rod 8 to the gauge-mark 7 on test-bar. Levers 10 and 11 swing about a common centre. By this construction provision is made that the card is moved only by the displacements of 6 and 7 relative to spring 5. The play in connecting detail between *z* and 5, as well as the extension of the heads, are excluded from the record. The diagram does not show how the machine is supported by *z*; it is done by lever 11 and connecting-rod 9. The indicator 18 is operated by rods 16 and 17, as previously described (*77*, *180*, *193*) in roller apparatus, and transmits spring extensions, i.e., the measure of force, on a magnified scale to the card 15.

548. Leuner also used the principle of the bar-spring in his latest apparatus (1897), Pl. 11, Figs. 28–38. It is built up to a capacity of 11,000 lbs. (5000 kg). The scheme of the machine is shown by Fig. 391. It is operated by worm-gearing and screw 2–4, loads indicated by bar-spring (standard bar) 29. The extension of test-bar *z* between points 19 is transmitted by means of rods 15 and 17, racks of which cause the drum 10 to revolve proportionately to the extension between gauge-marks. This is done by driving the drum directly by 16 and 17; bar 15 transmits motion indirectly by gearing 14, the tubular loose rack 12 and the gearing 13, which gears with a crown wheel on the rim of the drum. The spring fixed to the axis of drum revolves the latter loosely mounted on the axis, thus taking up all lost motion of the gearing. The drum and its driving mechanism are carried by plate 7. This plate 7 is connected to one end of the bar-spring 29. A steel band 25

is connected to the other end of 29 and a lever system 26, 27, mounted on knife edges, which records extension of bar-spring, magnified 150 times, by means of pencil 28. In this case also, secondary strains in holders and in heads are excluded from the record. Nevertheless the Kennedy-Ashcroft (*547*) apparatus should exceed the Leuner in accuracy and reliability, because more attention has been paid in the former than in the latter to sources of error arising from the construction.

549. Leuner has also simplified his machine by observing the indication of force applied on the bar-spring, by means of a telescope and mirror, Pl. 11, Figs. 39–49. Arms are provided on the cross-heads 5 and 7 on which the bar-spring 6 is fixed, one of which, 5, carries the mirror-support 10, while a clock-spring, 9, is attached to the other, 8, and wrapped about the roller of mirror 10, and strained by a spiral spring at the other end. The extension of bar-spring (load-indicator) is read as revolution of mirror by the telescope 15 on a scale. The design here used, which is very useful, may be improved in several ways. It conflicts with the requirements that extensions should be determined simultaneously on opposite elements, and to make flexure of the bar and change of position of parts of the machine, in space, harmless. The great distance of the tension-band 9 from the axis of test-piece must lead to flexure. Attaching to connecting points on the cross-heads 5 and 7 must also lead to uncertainty. Reading by but a single mirror does not admit of the accuracy obtainable by mirror apparatus (*94 b*, *700*). The same objections naturally apply equally well to measurements of deformations of test-pieces with but a single mirror mounted on one side of the holders. The arrangement of this mirror 11 is the same as that of 10. I believe that better results might be obtained by simpler means. It will certainly be necessary to prove the machines as to their sources of errors.

The fundamental idea described in *546–549* may also be ap-

plied by using the members of existing machines as springs for recording force. This is possible in all cases where a member is positively strained in an invariable manner, as is the case with straining-screws, scale-levers, or other parts subjected only to tension, transverse, crushing or torsional stress. I have used this idea for a time with the Werder machine. If it be skilfully applied, it may lead to very simple machines of great power.

Fremont made use of this principle, carrying out an idea similar to that of Hunt (*217*), using the elastic deformations of a machine-frame and the work done in punching metal plates to produce a diagram by means of an automatic recorder (*L 256*). The forces (deformations of machine-frames) are recorded by a largely magnifying lever system acting on a pencil, on a card moved by the motion of the punch or shears. The objections previously made (*217*) must be raised against this procedure, but one should not disregard the importance and value of the Fremont and Hunt propositions. The Henning Pocket Recorder has also been used for the same purposes, and is the simplest and most satisfactory apparatus ever applied to it. While the Fremont and Henning Recorders are directly applicable to any machine, the Hunt is designed for a hydraulic machine, and is subject to additional errors, and applicable only to hydraulic machines.

d. Load-indication, Hydraulic.

1. Gauges.

550. The simplest method of measuring force is that of measuring the pressure in the hydraulic cylinder of the testing-machines. It may be done by gauges of well-known types, especially by spring-gauges for high pressures, or mercury-gauges for small pressures. There can be no doubt that the construction of our testing-machines might be greatly simplified if it were possible to perfect this measure-

ment so as to reduce the errors of load-indication to less than 1 %.

That it is not hopeless to arrive at this condition I have repeatedly demonstrated (*476*). It is necessary to make piston-packing frictionless (Amagat, Marié, Amsler), or that the packing friction be known (Marié, Flad, Hick), and that care be had that it be eliminated (Amsler, Wicksteed) or be maintained uniformly. It is furthermore necessary to employ gauges which are as nearly accurate as possible and permanent in indications (double-spring gauge, mercury-gauge); spring-gauges must therefore be protected from sudden variations of pressure (*412*).

Gauges are such well-known instruments that it will suffice to discuss them only in so far as they are of interest in testing materials (*L 234*).

551. For direct measurement of pressures in hydraulic cylinders it is always a question of high-pressure gauges, hence of the Bourdon tubular steel spring-gauges. Very reliable and sensitive Bourdon gauges for pressures up to several thousand atmospheres may be had, but they should always be used in pairs (duplex gauges, standard gauges) simultaneously, in order to indicate any change instantly. The Testing Laboratory has lately had its gauges graduated, not in atmospheres, but in circular scales, and a table of values of readings is obtained from actual trial for each gauge, from which loads are obtained directly. This has been done because graduated circles are more neatly made than the coarse dials furnished by the gauge manufacturers, and because more accurate readings can be made. In future the dials will be mounted on a pivot, so that they can be adjusted to zero in case of changes in the multiplying mechanism. In order to make such changes instantly visible, the stops have been removed from many instruments in the Laboratory; each change then becomes the cause for

recalibration. Besides this, all instruments are calibrated regularly.

Attention may be called to the fact that the Physico-Technical Imperial Institute at Charlottenburg is admirably equipped for calibrating gauges, and that orders for such calibrations are executed very cheaply. Recently Wiebe published a report thereon (*L 234*). The author gives a résumé of the very instructive results which were there obtained by calibration of gauges. It may be accepted from his statements that the accuracy of indication of high-pressure spring-gauges is as a rule far within 1%. High-pressure gauges belonging to the Imperial Institute, repeatedly tested at various times, required the corrections below at 200 at. pressure:

Test	1	2	3	4
a	− 1.25	− 1.51	− 0.79	− 0.90
b	− 0.11	− 0.39	+ 0.33	+ 0.11
c	+ 0.02	− 0.24	+ 0.06	+ 0.09

The variations in the results of repeated calibrations may be considered very small for our practical purposes. Moreover, the corrections for gauge *a* might be reduced materially if it were provided with an adjustable dial (*551*), because the corrections deduced from all the series of observations are all negative and almost identical; they would have been greatly improved by shifting the zero point (*543, b*).

Wiebe estimated the probable error of a single reading in his test as about ± 0.05 kg (= 0.11 lbs.). Thermal changes produced variations of gauge-readings in his tests of + 0.04 lbs. for 1° C. up to 100 at. pressure.

For direct record of force the numerous existing recording-gauges may be used, and several types have been used for this purpose. I shall refer to one or the other of these presently.

552. Spring-gauges have been frequently used for indicating force. I mention one of the earliest testing-machines, that of J. Whitworth & Co., Manchester (1850); its plan is shown by Fig. 391*a*.

553. Gauges, and especially mercury-gauges, are largely used after a greater or less reduction of pressure. This reduction is obtained by intermediate levers or by hydraulic devices. The hydraulic reducers are, however, not always

attached directly to the press, but they are frequently combined with the gauge (*561, a*). This is the case in the large machines designed by Kellogg, described in (*473* and *474*). I wish to discuss these arrangements later on in common with hydraulic chambers, etc., without regard as to whether the pressure is measured in the power-cylinder or in a special hydraulic load-indicator. I shall also at that place discuss the details of construction of mercurial gauges. At this place I shall merely revert to the facts given in (*65, f*), and especially emphasize that the objection made against the use of mercury-gauges, that of thermic changes, does not appear to be justified, because the expansion is too slight. The coefficient of expansion for 1° C. is

$$3\alpha = 0.00018153;$$

hence the error in % for a thermal change of 20° C. would be only 0.36, while we have repeatedly considered 1 % as admissible. Thermal changes of 20 % are rare in laboratories. The errors of reduction in scales and in readings might, as a rule, exceed the error due to thermal changes, and the latter may be made very small by using a scale correct for average temperature.

It must not be forgotten that readings of mercury-columns may become somewhat inconvenient when the length of the latter is great, and that the errors of readings may, for this and other reasons (variability of illumination, unrest of the meniscus, irregularity of the meniscus, etc.), be different at different parts of a long gauge. It is therefore still a question whether the more convenient spring-gauges should not be preferred, more especially if it be considered that acceleration of mass of a thick column of mercury makes it overshoot the mark, and indicate an excessive height, if it is necessary to take readings on the moving column. In machines with mercury-gauges it will be necessary to observe that the speed of rising does not become too great if errors due to accelleration of mass should become small.

2. Hydraulic Transmitters and Chambers.

554. As I do not consider it important to give a systematic presentation of types as to whether the reduction of pressure is one of diminution or the opposite, I shall add what I have to say to the descriptions of such constructions which are used in connection with testing-machines. I shall take them up as it suits my purpose, in small variety.

555. In the Thomasset machine (*L 102*, II, 183, p. 23) the hydraulic reduction is used in its simplest form; I shall call it briefly a hydraulic chamber. The principle of the machine is shown in Fig. 392, its construction on Pl. 15, Figs. 3–6.

It is driven by a hydraulic press 1 with a packed piston, applying tension-loads to the test-piece. A long adjustable screw 4 passes through the piston, and can be advanced by nut 2 and hand-wheel 3, permitting it to be adjusted to length of specimen placed between 5 and 6; the latter are guided by the machine-frame. The load is transmitted to the hydraulic chamber 8 by means of the angle-lever 7. The cover of chamber may be loaded by calibrating-lever 10, which permits ready calibration of readings of gauge 9 simply and readily at all times. Screw 11 is provided for releasing pressure on cover-plate of chamber.

The hydraulic chamber in the 25-ton machine has an effective area of 465 sq. in. (= 3000 sq. cm); it acts on the mercury-column in gauge 9, which must rise 60.3 in. (126 cm) and requires 0.55 cu. in. (9 cu. cm) of mercury. Hence the rubber diaphragm of the chamber bears the small pressure of 1.66 at. (= 23.7 lbs. per sq. in.). Hence the lever-ratio for a capacity of 25 tons must be equal to $\frac{55000}{465 \times 23.7} = \frac{5}{1}$. The motion of the cover of the chamber is $\frac{0.55}{466} = 0.00117$; in this case it is so small that great sensitiveness of hydraulic chambers may be expected.

555a. However, doubts about the reliability of such hydraulic chambers have often been expressed, and very few systematic and exhaustive investigations of the accuracy and sensitiveness thereof have been published, although the great interest of the manufacturers of such machines is apparent. Even in the country where they have been in use for a long time, and in considerable numbers in France, competent authorities express doubts. The French Commission d'Essais says, through its sub-committee, H. Lebasteur and P. Arnould (*L 102*, II, p. 356) as follows:

"A fundamental difficulty is the uncertainty of determination of the force. The height of column may be measured accurately; but the area of the diaphragm or of its effective area is not measurable, because effect of the free unsupported ring of rubber on ratio is not known. Moreover, this part may vary during a test, because of pressure which changes the shape of the rubber. It is equally important to state that the presence of all air-bubbles in the chamber and tubing must be avoided."

From these expressions it is not possible to say whether they are experimental facts or merely opinions. This is to be regretted, as it is in France, where many types of machines use the hydraulic chamber, that the first opportunity was had of accurately testing their conditions and principles of construction. That this has not been done seems to me evident from the contradictions of the above-named report, and from the fundamental differences in use of hydraulic chambers. To elucidate these conditions I must discuss the subject somewhat; it seems to be of sufficient importance to warrant it.

556. A few pages further on the two French reporters refer to the calibration of testing-machines by hydraulic dynamometers of the P. L. M. R'y, and describe the apparatus shown on Pl. 15, Figs. 8–14. In these instruments the rubber diaphragm is replaced by sheet brass. The structural

proportions are: thickness of brass = 0.0077 in.; area of chamber 6.84 sq. in.; highest pressure in the chamber $p = 500$ at., corresponding to a total load of 44,000 lbs. The pressure is transmitted to a Bourdon gauge, permitting readings of 110 lbs., or about $\frac{1}{400}$ of the total load.

This apparatus is praised by the reporters in an extraordinary manner. It is said to have given great satisfaction during long-continued use, and is said to be particularly well adapted for calibrating testing-machines as to their accuracy. I shall certainly take an early opportunity of examining this apparatus in an exhaustive manner.

According to the foregoing, the lack of uniform reliability when using rubber diaphragms cannot be a matter of principles of construction. In my opinion it is not a matter of the possible presence of air-bubbles; they can be easily avoided by using boiled water, and arranging the chambers in such manner that they can be heated to 212° F. while being filled. The air-bubbles would then be easily expelled. The indefiniteness of the dimensions of the unsupported part of the diaphragm I can hardly consider as a serious source of error, or of variability, with correct design. The principal errors are to be found, as a rule, in the improper use of the rubber diaphragm, because its properties are not properly considered. And these errors, as far as is noticeable from the designs with which I am familiar, exist in the Thomasset as well as the Maillard machine (*557*).

If rubber is to be used [thin sheet metal is undoubtedly more suitable, because it can resist high pressures ($p = 500$ at., see above)], it should not be clamped as in Fig. 393, but as shown in Fig. 394. The clamping-ring 3 always causes the rubber to swell into the space, and it is then jammed easily into this ample space *a*, Fig. 393, and thereby prevents the free motion of the plate 4; if the pressure becomes great, the rubber may act as a wedge in this annular space. In Figs. 394

and 394*a* this swelling between 1 and 2 is made harmless; it is well to round off a little the corners of 3 and 4 in contact with the rubber, and to make the space as narrow as is just sufficient for easy play of the cover. It is natural to suppose that the cover assumes its correct position, so that the rubber diaphragm is perfectly flat under the minimum pressure. The greater the necessary motion of the cover, the greater must be the width of space *a*, and the less will be the maximum pressure *p* allowable in the chamber.

I used a hydraulic chamber after the manner of Napoli, shown in Fig. 395, $\frac{1}{10}$ scale, for my lubricant-tester (*L, 230*). The base 1, with cover 2, can be screwed into the pressure-chamber of the oil-tester by means of screw 6. 8 is a set-screw. In screwing it home the loosely moving plunger presses upon the journal-box 10. The pressure applied is transmitted to plate 4, thence to the liquid sealed by the rubber diaphragm 3. The liquid pressure is then read off by the gauge 9, the reading of which indicates the pressure applied to 10, which can be increased to about 5500 lbs. (2500 kg). Five of these hydraulic chambers were calibrated repeatedly at different times. These calibrations were made as shown in Fig. 396 in the 50-ton Martens machine of the Charlottenburg Testing Laboratory, by comparing the gauge-readings with the loads on the machine. I here reproduce the results because they may be of general interest.

Table 41 gives the mean values of individual calibrations of sets of five series, and below is given the number of variations from the mean value of the series of values given in the first part of the table. The values in the table have then been used to plot the diagrams in Fig. 397.

The principal series I in Table 41, curve A, Fig. 397, relate to different rubber diaphragms, which were used with the same gauge in the same hydraulic chamber. The lines are generally parallel, but not perfectly rectilinear. From this it may be deduced that the ratio of the chamber is not

Table 41. Calibration of Hydraulic Chambers of several Lubricant-testers, Martens Design.

Gauge-readings for loads in kg inscribed above.

In Group I gauge and chamber were in every case the same; in Group II gauges and chambers only were of the same type.

Machine No. and Remarks.	Date of Test.	Loads in kg. 250	500	750	1000	1250	1500	1750	2000	2250	2500
I. Testing Laboratory Machine.											
a) (Chemnitz Machine Works) New.....	24./6.87	0.652	1.200	1.808	2.375	2.938	3.495	4.070	4.660	5.208	5.723
b) New rubber disk inserted............	23./2.91	582	156	750	342	888	464	042	660	178	714
c) do.	7./9.92	532	134	764	366	944	528	138	762	332	906
d) do.	18./1.93	616	190	770	356	904	478	068	662	230	774
II. Machine built by Ludw. Loewe.											
Tested under A, No. 5130	Oct. 93	0.480	0.870	1.350	1.790	2.230	2.700	3.100	3.550	3.970	4.400
Tested under A, No. 5371	8./3.94	450	880	280	790	140	560	990	410	820	220
Tested under A, No. 5371, 2d test	19./10.94	440	850	290	750	150	580	000	410	820	220
Machine No. 10855, No. 6910*a*	22./4.95	366	810	254	672	052	436	810	198	578	952
Machine No. 10856, No. 6910*b*..........	22./4.95	390	776	228	652	050	492	886	348	758	170

Values given in kg because the calibration is shown as well as in British or U.S. wts.	Variations in at. 10^{-3} from	to	Frequency of the variations from the mean value of the sets of 5 series, from which the above averages were obtained.										Mean at. 10^{-4}
	over	+100	—	—	1	—	—	—	—	—	—	—	1
	+ 80	+ 99	—	—	0	—	—	—	1	—	—	1	2
	+ 60	+ 79	—	2	1	—	—	—	0	1	2	1	7
	+ 50	+ 59	—	0	1	1	1	1	0	1	0	0	5
	+ 40	+ 49	2	1	1	1	0	1	2	3	1	2	14
	+ 30	+ 39	1	3	0	0	0	1	3	3	0	0	11
	+ 20	+ 29	3	4	2	3	1	1	0	1	12	7	34
	+ 10	+ 19	5	4	5	3	13	7	6	2	3	0	48
	+ 0	+ 9	10	7	11	11	9	12	9	7	1	5	82
	+ 0	+ 9	9	7	5	11	8	8	9	11	8	10	86
	+ 10	+ 19	2	0	2	2	0	1	3	3	9	7	29
	+ 20	+ 29	0	4	3	2	2	4	0	1	2	2	20
	+ 30	+ 39	2	1	2	2	2	1	2	1	0	0	13
	+ 40	+ 49	4	0	3	0	1	1	1	3	0	3	16
	+ 50	+ 59	1	3	1	1	1	0	1	0	0	0	8
	+ 60	+ 79	1	2	1	0	0	0	1	0	1	0	6
	+ 80	+ 99	—	—	—	1	1	1	0	0	0	0	3
	under	+100	—	—	—	—	—	—	1	1	1	1	4

materially altered by the insertion of new rubber diaphragms, that hence the effective area of the chamber, i.e., including the ring of unsupported rubber, has not been materially changed. It would be possible to make the lines in group A more nearly

coincident by parallel displacement. The new rubber disk, probably mainly due to the circumstance sketched in Fig. 393, produces a displacement of the initial point of the lines, but their inclination is only slightly changed. The width of unsupported ring was in all cases the same, and was about 0.117 in. (= 0.3 cm); the thickness was not measured, but was about 0.117 in. = 0.3 cm).

Besides the errors produced by the disks, the errors of graduation of the gauge-dial influence the shape of lines in group A, Fig. 397. To study this effect I have calculated the series of differences between the series, and also plotted them in group D. It becomes apparent at a glance that the dial could not have been properly graduated, unless the irregular shape of the lines is to be laid to errors of the testing-machine. This is, however, highly improbable, as the machine has always been shown to be perfect during calibrations. The thick line of averages for the four series with different rubber disks will therefore represent the errors of the gauge with quite a degree of probability.

If these errors were eliminated by re-graduation of the dial, the lines in group A would have to be replaced by right lines of the equation

$$P = \pm a + bn,$$

in which n is the gauge-reading, and b the ratio of the diaphragm, while the constant a depends upon the character of the rubber disk or on the position of the zero-point of the gauge.*

It is of interest to have an illustration of the degree of accuracy which observations made by means of an hydraulic chamber may possess. Without tedious calculations, the group of lines B, Fig. 397, illustrates this point. It is obtained by calculating the variations from the particular mean value of all the available data (Table 41, nine sets of five series), and then determining for the different loads the number of positive and negative deviations, and then plotting the curves of frequency of different values of errors as in group B. A first glance shows, what is explicable from the fore-

* In this case a movable dial with graduated circle (*551*) would be of great service, because the value of a might then be made equal to 0.

going, that the errors as a whole are not appreciably affected by the intensity of the loads; the curves are similar to each other, and irregularities appear only under high loads (2250 and 2500 kg). This demonstration makes it seem permissible to calculate averages from all groups of errors noted. These averages are plotted in group C, Fig. 397. The probable error of observations may be estimated therefrom by eyesight without resorting to calculations. It is that ordinate (value of error) which would divide the area enclosed by this curve of frequencies on the positive or negative side into two equal areas. Hence the probable error, according to curve C, Fig. 397, would be estimated at a little less than 30.10^{-3} at., i.e., $r = \pm\ 0.030$ at. If it is desired to express it in % of the readings n (also of the measured loads P), it would naturally decrease with increasing loads. For expample:

$$\begin{array}{lcccccl} \text{if } n & = & 1 & 2 & 3 & 4 & 5 \text{ at.} \\ r & = & 3 & 1.5 & 1.0 & 0.75 & 0.6\ \%. \end{array}$$

Hence an hydraulic chamber of the type tested would not be satisfactory for delicate measurements, unless corrections based on constants of the apparatus, previously determined experimentally, be applied. The degree of sensitiveness is dependent upon the kind and accuracy of gauge-dial; if the gauge be divided into 0.1 at., and 0.01 at. might be estimated, this would mean for a mean reading of 0.575 at. = 250 kg an estimation of $P = \dfrac{250 \times 0.01}{0.575} = 4.4$ kg. The degree of sensitiveness of an hydraulic chamber may also be called that increment of load ΔP which must be added to any load to cause the gauge-indicator to move over one division of the dial. This degree of sensitiveness varies with the load, and is different under increasing and decreasing loads; it can only be determined by tests, which were not made in the series discussed.

557. Maillard also used a hydraulic chamber for measuring loads in his machine (*L 102*, II; *183*, p. 17; *209*). The scheme of this machine is shown in Fig. 398, and its construction on Pl. 15, Fig. 23.

It is operated by the hydraulic cylinder 2, with a packed piston 3 acting directly on the test-piece. Pressure is generated by a Desgoffes compressor in which a bucket plunger of about 10.85 sq. in. (= 70 sq. cm) area is forced into the cylinder by worm-gearing. The available stroke is 23.4 in. (= 60 cm), and maximum pressure required is about 80 at.; a single stroke delivers about 256 cu. in. (= 4.2 litres) of water.

co: ...27, and the holders 9
pr ... 12. The adjustable
pr ... position.
th ... draulic chamber 16, also
su ... phragm seals the chamber
o. ... ver-plate 19. The frame
al ... the plate 19, and swings
... aulic chamber is held in the
at ... se provisions for motion are
F ... ins in the test-piece. They
fo ... ver, and it is at least ques-
I ... ult is not thus attained. I
p ... mply and safely, and to pro-
h ... g-stress in the holder. The
l. ... each 80 at., judging from the
l ... scribed it was transmitted to a
... ge (L 234) the lower chamber
... disk on the small surface of a
... surface, similarly sealed, acts on
... (= 0.4 cm) diam., which may

... height of this column corresponds
... ne, 55,000 lbs. (= 25,000 kg), the
... e will amount to about 0.10 in.
... might still be read off, provided
... m suffices. The total volume of
... = 1.098 cu. in. (18 c. cm). The ratio
... maximum length of column and
... chamber $n = 80 : 150/76 = 40 : 1$.
... the piston is $\frac{1}{40}$ = 0.0027 cu. in.
... meter of chamber = 7.88 in. (= 20.2

... cover will rise $\frac{0.0027}{49.5} = 0.000546$ in.

... the sensitiveness may therefore be in-
... of rubber diaphragms be employed

that the clamping-ring does not cause it to become upset, and by making provision for frictionless play of the movable parts. Simpler, of course, than the mercury-gauge used, and probably just as reliable, would be duplex spring-gauges which control each other (*551*). Their scales may easily be 8 in. (200 mm) long, and when reading to 0.009 in. ($= \frac{1}{4}$ mm) this would correspond to an estimated load of about $\frac{55000 \times .00975}{8} = 67$ lbs. Safe recoil-valves should be provided in every case (*412*).

If test-pieces up to 24 in. (60 cm) length are to be tested, the hydraulic chamber mounted on the slide 21 may be shifted by means of screw 22 and hand-wheel 25.

558. E. Chauvin and Marin Darbel, Paris (*L 102*, II ; *183*). In this machine the loads are also measured by a rubber disk chamber, which is, however, loaded in a sense opposite to that ordinarily provided for. Generally increase of stress in the test-piece produces increase of pressure in the chamber ; in this the pressure is diminished. The load on the bar *z*, Fig. 399, is reduced by lever *H* to $\frac{1}{8}$, and transmitted as a tension on the cover-plate of the chamber, and read off by reduction of pressure on a vacuum-gauge. By this method extravagant dimensions of hydraulic chamber are required, because the available differential pressures in the chamber between 0 and maximum load are small.

Pichler described and illustrated a 66,000-lb. (30,000-kg) machine (designed 1878)* on $\frac{1}{10}$ scale, from which I take that the diameter of chamber was about 37 in. (= 95 cm), area = 465 sq. in., in which the difference of pressure would be 0.86 at. Did the chamber work satisfactorily under these conditions? Pichler states that the machines were built of 15, 30, 60, and 100 tons capacity.

* I could not obtain accurate data about later constructions ; the report of the Commission d'Essai, Tome II, p. 356, 1895 (*L 102*), refers to it but briefly.

559. Hydraulic chambers were most completely developed and perfected by A. H. Emery. He and the firm of Wm. Sellers & Co., Incorporated, Philadelphia, Pa., employ them extensively in testing-machines, and, as an indisputable fact, most successfully. The construction of the Emery machine as built by Sellers is shown in detail on Pl. 18 and in (*623–635*); other types are shown by Fig. 344 (*483*) and Fig. 356 (*504*). In Figs. 400*a* and 401 are shown the Emery type of hydraulic chamber as used in vertical machines. The chamber consists of two thin brass disks, soldered at the edges and pressed into the ring of solder 10 into a groove in the base 1. This base and the cover-plate 3 are provided with circular and radial grooves, into which pressure forces the brass disks, forming channels for the ready distribution of liquid throughout the chamber. The source (*L 219*) states that the layer of oil is but 0.02 in. (0.5 mm) thick. The large chamber is connected with a smaller one in the scale-case. This system of chambers, therefore, replaces levers in reducing loads transmitted. The tubes and chambers are connected in the manner shown in Fig. 401. The perforated plug 4 is soldered to the lower brass sheet of the chamber by means of the ring of solder 11. The tube 7, of about 0.06 internal diameter, is then connected by conical plugs and seats 5 and 6. This tubing, it is said, may be carried to a distance of 27 miles (??). Emery's effort to reduce the quantity of liquid and its motion in the pipes, evidently to avoid thermal effects and frictional resistances as much as possible, is apparent.

The essential peculiarity of the Emery testing-machine is the method by which the stress produced upon the piece tested is conveyed to the scale and accurately weighed by mechanism that is entirely frictionless, and hence responds to the same increment of load regardless of the amount of stress upon the specimen. This result is accomplished by receiving the load upon a flat closed cylinder called the "hydraulic

support." The general scheme is indicated in Fig. 400, which shows merely the relation of the parts, no attention being paid to proportion.

The depth of the hydraulic support-cylinder *A* is exceedingly small; the end is closed to prevent the escape of the contained fluid by a thin sheet of metal, *b*, upon which rests a piston, *c*, considerably smaller than the internal diameter of the cylinder. This piston is secured to the cylinder by thin flexible fixing-plates, *dd*, which permit a very small movement in the direction of the axis of the cylinder while rigidly securing it against any lateral movement. This longitudinal movement of the piston from no load to full load is not more than .003 inch, and as there is no hydraulic packing and no sliding, there is no friction beyond that of the fluid. This hydraulic chamber is connected by a pipe, *e*, with a smaller but similar chamber, *B*, placed in the scale; the piston *c'* of this latter chamber acts through the block *H* against the first lever *C* of the scale, which thus receives a fraction of the load upon the piston *c* determined by the relation between the areas of the two hydraulic cylinders *A* and *B*.

The scale-body is a rigid cast-iron frame carrying the steel scale-levers, all the supports and connections of which are thin flexible plates of steel firmly secured to the levers and their supports, and having a sufficient exposure between their fixed ends, that the amount of bending due to the movement of the levers shall be well within the elastic limit of the material. The long arm of the lever *C* is coupled by the bar *D* with the short arm of the poise-frame lever *E*; the long arm of this lever carries all the standard weights of the scale, and the method of putting them on or taking them off, without handling, is peculiar to the Emery system. Suspended from this lever, *E*, at suitable intervals by thin fulcrum plates are "poise-frames," *N*, consisting of an upper cross-head, *S*, and a lower cross-head, *T*, united by three vertical bars disposed at equal intervals about the cross-heads.

559. Hy... ...nner faces with short
oped and ... ...zontal surface and a
of Wm. S... ...milar surfaces formed on
phia, Pa., ...ers or rings with bevelled
as an indi... ... the flat surfaces and
of the Em... ... A "weight-frame," *M*, for
tail on Pl. ... ...se, of similar construction,
Fig. 344 (... ...s alternating with the bars
shown th... ...ame is guided and is raised
vertical ... ...ut touching the poise-frame,
disks, so... ...oupled to the rod projecting
10 into ... ...rackets on the weight-frame
plate 3 ... ... those on the poise-frame, and
which pr... ... top of its stroke it carries all
ready ... ...oise-frame; a small movement
source ... ...ght to the poise-frame, the
mm) ... ...ckets centring the weight if it
one in ... ...y a too sudden movement. A
places ... ...nother, and so on; that is, the
chamb... ...e in either direction transfers the
The ... ...ly from one frame to the other;
the c... ...n carried by the poise-frame, *j*
of ab... ...while *h* is being transferred from
plug...
ried ... ...er is provided with a notched seg-
redu... ...ring plays so that the operator feels
evid... ...ver the right distance to transfer a
mu... ...se-frame without having to watch the
... the arrangement of the six bars sur-
is ... ... cage that effectually prevents any
te... ...sequent interruption of the test, as
m... ...re the weights rested on simple shelves
th... ...ected pins. There is hence no neces-
up... ...ass case that encloses this part of the
th... ...hts are never exposed to any risk of altera-

tion. The weights in the first poise-frame have a value of 100 pounds, the next frame carries weights of a value of ten times as much, or 1000 pounds, the next 10,000 pounds, and so on, and the readings are summed up by a series of segments connected to the several operating shafts and provided with figures denoting the number of weights on each poise-frame. A horizontal slot in a vertical plate near the upper left-hand corner of the scale is so placed that the reading of the figures shown through this slot denotes the number of pounds pressure applied to the specimen.

The final lever of the scale is an indicator-needle, F, which has a movement at its point of $1\frac{3}{4}''$ to $2''$, and this movement, calculated from the mechanical ratios of the hydraulic chambers and of the levers in the scale, is not less than 300,000 times the movement of the piston c in the first hydraulic chamber, and may on large machines be 6,000,000 times as much. The transfer of fluid from one chamber to the other is almost imperceptible.

From the proportions and statements made (*L 219*) the internal pressure in the support of a 50-ton machine can be derived as about 60 at. It is stated that the play of the main support-piston in such a machine is, as a maximum, 0.000002 in. = 0.00006 mm), hence the displacement of liquid in a support having on area of 124 sq. in. (= 800 sq. cm) is equal to 0.0003 cu. in. (= 0.005 c. cm), and the total motion in the tube of 0.048 in. diam. (= 1.25 mm) will be about 0.156 in. (= 4 mm). I have unfortunately not been able to find any statement of thickness of the sheet brass. The width of the unsupported ring between base and support-piston is shown to be about 0.08 in. (= 2 mm).

Rectilinear motion of the support-piston is secured by Emery by use of annular diaphragms 9, Fig. 401, and 10, Fig. 402, secured by solder in grooves. Fig. 402 shows an hydraulic support of a railway platform-scale.

a. From the previous Sections 554–559 and the success of the Emery machines, it will be seen that the use of hydraulic reduc-

tion by differential chambers offers material advantages, because very simple and compact machines can undoubtedly be thus constructed, especially if it should succeed to use them in connection with simple spring-gauges. I have been personally busy with this idea for years, without having been able to perfect it, because of preoccupation. As my frequent propositions to manufacturers remained fruitless, I desire to publish them in this place. I am convinced that it will be possible to build reliable machines, having an error less than 1%, based on the principle of hydraulic chambers, for there is no reason to assume that, with proper construction and use under moderate loads, hollow springs (Bourdon tubes) will not work as reliably as spiral springs in the indicator, or in the paper-testing machines of Hartig, Wendler and others.

b. Years ago I commenced an investigation of the resistance and sensitiveness of thin sheet metal in such chambers, but could not complete it for lack of time. In these tests I found that the permissible stress is rather high, and that the sensitiveness, even under motion, great for the intended purposes, seems to be ample. From the results of tests a few are here selected; the completed investigation will be published later.

The first tests were made on a hydraulic support placed in the 100-ton Pohlmeyer machine, and it could be loaded up to 790 at. pressure. The diameter of chamber was 3.63 in. (93 mm), and of piston 3.39 in. (87 mm), making the width of unsupported ring 0.12 in. (= 3 mm). Plates of various materials, of 5.34 in. (= 137 mm) diam. and of various thicknesses, were placed in flat condition into the chamber, and pressure applied either up to rupture in the unsupported part or to 790 at. pressure. Sheet copper of 0.004 in. (= 0.1 mm) thickness showed pronounced permanent buckling at 27 at., rupture occurring at 173 at. With a thickness of 0.008 in. (= 0.2 mm) they failed at 318 and 356 at.; two plates 0.019 in. (= 0.5 mm) did not fail, but were considerably buckled at 790 at. pressure. Sheet brass, 0.007 in. (= 0.188 mm) thick failed at 460 and 540 at., and carried 790 at. pressure at 0.009 in. (0.23 mm) thickness, without failing, but were considerably buckled. Sheet steel 0.0074 in. (= 0.19 mm) thick failed at 255 at. and was but slightly buckled by pressure of 790 at. when 0.019 in. (0.5 m) thick; likewise sheet zinc, 0.036 in. (0.92 mm) thick. From this, soft sheet brass seems to be a material specially suited for hydraulic chambers. The figures show what great pressures are permissible in them, and will recognize their advantage in construction of testing-machines. It is to be hoped that a continuation of the investigation will also demonstrate sufficient sensitiveness and reliability in indicating loads.

560. Amagat (*L 102*, II, p. 109, Pl. X) constructed a small machine for determining the crushing-strength of small

copper plugs, in which a plunger-press served as a hydraulic support. It is operated by a screw 7, Fig. 403. The pressure is transmitted to the test-piece by a nicely fitted hardened steel cylinder 6 guided by the machine-frame, thence to a similar cylinder 5 bearing on the column 5, which rests on the plunger 3. The plunger 3, of about 13 in. diameter (330 mm), has a grinding fit in cylinder 1, which is provided with circumferential grooves for the castor-oil, which issues between plunger and cylinder. The castor-oil floats above a layer of mercury, which is connected to an open gauge 8, 17 ft. high (4 m). The friction between plunger and cylinder is eliminated by turning the plunger through an angle of from 20° to 30° by means of the handle 10. Loads up to 4500 kg can be measured; but reading a 17-ft. mercury-column is by no means an easy matter.

561. Amsler-Laffon (Pl. 14) in his machine based measurement of loads on precisely the same principle, only he reduced the liquid pressure so as to make possible the use of a short mercury-gauge for greater loads; he measures the pressure in the hydraulic cylinder, while Amagat does it in a separate chamber.

The construction of the Amsler device is shown in Fig. 333. The pressure on the castor-oil under the plunger 27 is transmitted by the small plunger 26 to the larger one, 3. The pressure, reduced in ratio of diameters of plungers, acts through the piping 4, 5 on the mercury-gauge, the scale of which is divided on one side into kg and into stress referred to a standard cube of cement or mortar, having a length of 7.1 cm. The plungers 3 and 26 are made to reciprocate by means of lever 28, and rod 30 by wheel 35. Friction is thus again eliminated on the Amagat principle. The mercury-gauge is provided with a float whose weight is almost exactly counterbalanced by a weight. Its connector passes over a small sheave having a delicate brake, which prevents dropping of the float, and makes it possible to take maximum readings

after test. The motion of this sheave is used by Amsler to transmit load-indication to his autographic recorder (*719*).

Refilling the oil which escapes slowly between plunger and cylinder-walls is accomplished by the pump 45 or the pipe 46.

561a. Amsler-Laffon also constructs his pressure-reducer as an independent apparatus to be used in connection with testing-machines as shown in Pl. 14, Figs. 6 and 9. The reducer is shown mounted on the frame of the pressure-pump. The principle of construction is the same as described in (*561*) and illustrated by Fig. 333, only that a third plunger, 4, is used additionally to 3 and 5, Fig. 404, and so designed as to be ordinarily caught by its projecting rim in the chamber of the casting, and become inactive. The pressure from the press conveyed by pipe 22 is transmitted by the small plunger 5 to the larger, 3, and is reduced according to ratio of plungers. Oscillatory motion is imparted to both plungers 3 and 5 by a sleeve and lever 9, 3 being operated by a long feather on the sleeve, while 5, its lower end, engaging a rib on 3, is carried around with it. If the ratio of reduction is to be changed in the hydraulic chamber, all that is necessary is to force considerable oil into the space 11 by the pump 14. This raises plunger 3 until the rib on lower end of 4 enters a groove in 3, thereby giving 4 free motion. Plungers 4 and 5 will then act as a unit, and the ratio of reduction is thereby decreased. Otherwise its action is the same as described in (*561*). The oscillatory motion is imparted by the pump. A rod 10 is mounted on 3, indicating the position of the latter, showing whether or not 4 is in action. Hence it may be seen on the outside of reducer which ratio is employed at the time. This condition is also noticeable on the mercury-gauge, so that the observer knows instantly which of the two reading-scales is to be used. In the 150-ton machine the principal scale is divided in 200 kg, and the second scale in 20 kg.

562. Unwin applied the hydraulic chamber with mercury-gauge in a very skilful manner, similar to that of Thomasset,

Pl. 15, Figs. 3–6, to construct a series of small machines which are admirably adapted for educational laboratories. I regret that I must abstain from a more detailed presentation thereof because of the lack of courtesy of the firm of Bayley & Co. in Manchester, who construct them. These small machines are arranged for tension-, crushing-, torsion-, shearing-tests, etc.

563. Exceedingly great ratios may be obtained by the use of hydraulic chambers, as minutely detailed in the description of my 50-ton machine (*L 162*). Although this device, for reasons stated in (*530*), is no longer in use, I wish to reprint the matter relating to the hydraulic chamber and recorder, because the experience obtained is in many ways instructive.

a. If the machine Pl. 5, Figs. 1–4, is to make the test automatically, the right-hand devices are made inoperative, by relieving all weights and disks and unloading the scale completely. The screw 58 at the top of the left-hand column 56 is raised until the knife-edge in the end of the lever bears on its seat when the lever stands in its position of equilibrium; the machine is then ready for operation. The test-piece 11 carries at its gauge-marks two spring-cushioned clamps having attaching screws with wedge-shaped ends, these marking the gauge-length. The lower clamp has an eye to which the string is attached, which passes over a roller on the upper clamp 89 (a very fine copper wire), then to the guide-rollers on the left-hand column, and thence to the recording-drum 84. These guide-rollers are adjustably attached on a rod fixed to the column. A part of the string leading off at right angles to the axis of test-piece, the independent axial motion of the test-piece (slipping in wedges), other than its deformation, is eliminated from the record (*534*), as well as the relative displacement of clamping-screws, the extension of gauge-length of test-piece, is alone recorded. If the bar is provided with heads, as in standard round bars, the relative motion of the pulling-heads may be recorded without causing any material error, and simplify the test somewhat. The recording paper

can be readily and quickly laid about the drum and held in position by brass springs. The drum revolves easily about its vertical axis, held by two pivots, and is readily removable. A small counterweight keeps the copper wire uniformly taut.

The load applied to the test-piece is transmitted by the scale to the column 56, which passes freely through the series of weights 51, bearing with its point on the hydraulic support 67, designed on the Emery system, Pl. 5, Figs. 8 and 9. The column is steadied at its upper end from the cross-head of the machine by the link 57, Figs. 1 and 2. The piston of the support is guided by two rings of metal 63 and 64, and its play is limited to a very small amount by the overlapping edge of the clamping-ring 60. The piston and the base of the support are conical, so that all air will escape through the hole in the bottom when filling with liquid in an inverted position. Before turning it right side up, after filling, the piston is secured rigidly in position by three radial set-screws passing through the outer and bearing against the inner clamping-ring 68. Thus the thin sheet-metal ring which seals the annular space between piston and base would be protected against distortion even if the guide-rings 63 and 64 were removed during filling. This is advisable so as to be able to warm the support by gas-flames placed below it while filling it. The sealing diaphragm is soldered, in grooves previously tinned, in the piston and in the base to insure absolute stanchness, a less fusible solder being used on the piston than on the base. In order to obtain well-defined action, the diaphragm is clamped exactly at the edges of clamping-ring and chamber. While filling the support, the air is driven out of the inverted support by slightly moving the piston and rapping it constantly; the water had been previously boiled. The base is then heated, until steam escapes from the rubber tube temporarily connected with the hole in the base; the other end of this tube is immersed in a dish of boiled water and the base is then cooled. This process is repeated several times, the permanent con-

necting pipe completely filled with boiled water, is connected, care being taken to exclude all air as much as possible, and the heating and cooling is repeated finally, after inverting the support, until all air has been expelled. It is absolutely necessary to obtain this condition if it be desirable to obtain proportional scale-readings for the records of load on the diagrams. A contact-lever is provided on the piston, which indicates its motion on a ratio of 50/1, and which was originally used as a contact-point for the electric circuit with unsatisfactory results.

b. The pressure produced in the support by the load on the test-pieces is transmitted by the water to a very thin skin, situated in the lower part of the chamber 75, 76, Fig. 8, which is the electric key, and seals the water in it completely. On the lower right-hand side of this chamber there is a very small tube provided with a stopcock and connected to a reservoir of water placed on a higher level. By raising or lowering this vessel the position of the piston of the support may be adjusted to that position in which it works best; the stopcock is then closed. Great thermal changes (summer and winter) produce difference in length of the piston. By means of this stopcock and the devices described, these changes of length may be provided for. The pressure of the test-piece is then transmitted by a hard-rubber rod to a second upper support, of identical construction, forming the electric key, thence acting, by means of an intermediate layer of water, on the mercury contained in a vessel at the lower end of left column, Fig. 3, and which moves in a carriage. The final connection with this vessel is a covered rubber tube. An iron disk floats on the mercury in the vessel, which serves to distribute the inertia of the moving mass of liquid in the tubes throughout the entire body of mercury, and to thus produce a most steady condition of the mercury. The mercury-vessel forms an hydraulic weighing-machine; it must be raised or lowered in proportion to the stress transmitted by the test-piece, in order

to equilibrate the pressure of the test-piece by the hydrostatic pressure within the support. In order to effect these movements of the mercury-chamber automatically, the hard-rubber rod above mentioned is provided between the diaphragms of the small chambers, its minute movements making and breaking a weak electric circuit, as shown in Fig. 405. The platinum pin *a* let into the hard-rubber rod effects contact as soon as it touches the platinum plate carried by the short arm of lever *b*; the latter is very slightly loaded by spring *c*, moving readily with the rubber rod. This produces a slight friction at the points of contact, making the latter more positive. The screw *d* serves to adjust the height of short end of lever, and makes it possible to find that position of the two small diaphragms in which they are most sensitive. A very weak electric current is used to protect the surfaces of contact. A condenser is also placed in circuit, which reduces sparking, at breaking of contact, to a minimum.

The current passes from the key to a relay, through the anchor of which a strong current is passed. This current operates the electromagnets of two clocks 85, Fig. 3, Pl. 5, placed in a common box; if the circuit of the first current is closed, the second strong current passes to the magnet M_1, Fig. 406; when the first circuit is open, the strong current passes to the magnet M_1. The magnets control the brakes of the clocks U_1 and U_2, and their operation in the first case is to break the left-, and in the second to brake the right-hand clock; hence the liberated clock comes into play. The left clock is operated by the heavy weight *P*, while the right is driven by the lighter weight of the mercury-vessel *Q* itself and its guide-rod. Therefore the test-piece will press with too much force upon the diaphragm when the first circuit is closed, and the mercury-chamber will rise until the mercury-pressure is in excess, and opens the first circuit. The play of the relay then becomes very rapid, and the mercury-chamber oscillates with very slight play about its position of equilib-

rium, which is recorded on the drum by a pencil attached to the guide-rod of the mercury-vessel. The position of equilibrium for zero load can be adjusted at will by opening the sealing-valve 75 at the upper point of the tubing 74 after adjusting the vessel to its desired position, and then adding or wasting the necessary quantity of water by tube 74. As far as this tube is of metal it is wrapped with cotton and covered with leather, because thermic changes of this part exert a material influence on the position of the zero-point, it being dependent upon the level of the mercury in the rubber tube.

The precautions here described were by no means originally provided, but were determined, as well as the circumstances still to be mentioned, only after numerous tests. It is therefore hardly inappropriate to discuss the most important experiences gained in this place in detail, because they may be valuable on other occasions. I shall follow a description of modifications which the apparatus underwent in course of time, previously published by me (*L 115*), because I could hardly describe the circumstances more briefly. It will suffice to refer to the diagrammatic illustrations shown in Figs. 406–408.

c. The first test of the device was made on a small 1-ton machine; the arrangement is shown by Fig. 407, and clearly explains itself. The weight G is slightly greater than necessary for the maximum capacity of the machine, and is secured to the chamber-piston D. The liquid in the chamber is in connection with the column Q, which just balances the weight G. When loading the test-piece, a part of the load G is transferred to it and the piston of D rises, until balanced by the mercury-pressure in Q.

d. As it is troublesome and not very reliable to take readings of the mercury meniscus throughout the test, the apparatus should record automatically. The type of recorder shown in Fig. 408 seems to be the most suitable of many forms possible for this case.

The difference in mercury-column is no longer obtained by the change of contents of chamber D, but by that of cylinder P, regulated by very slight motions of the piston of D, which control the relay R, by which and its magnets M_1 and M_2 the slide-valve S of the pump W is governed. The motion of the common piston-rod of P and W is a measure of differences of mercury-pressures, and for that part of the weight G carried by the test-piece. This motion is recorded on the drum T. The revolution of the latter is produced by the extension of the test-piece by means of the string Z.

e. The type shown by Fig. 406 is that originally used with this machine, and it will suffice to point out that the pump W is replaced by the clocks U_1 and U_2, arranged as previously described. Q is the mercury-chamber, Kr the contact-lever (see Fig. 405), and R the relay for the magnets M_1 and M_2 of the clock-brakes.

f. A common defect exists in all of these three types, which makes them useless for accurate measurements, or at least very inconvenient: the greater or less mobility existing in the chamber-piston. This is most disturbing in type Fig. 407, for in it the piston must always move proportionately to the mercury-column. This motion is in any case sufficiently great to bring a material source of error into play, the condition of the thin diaphragm due to deformation, and the action of friction of the mercury in the small tube connecting the chamber and the mercury vessel. If, for example, an effective diameter of chamber $d = 8$ in. (20 cm) be assumed, or about 50.26 sq. in. (= 300 sq. cm), a difference in load on piston of 220 lbs. (100 kg) would equal a mercury-column of 10 in. (= 25.3 cm). The internal area of mercury-tube must not be less than 0.077 sq. in. (= 0.5 sq. cm), and hence a drop of 10 in. in the mercury-column will cause a flow of 0.775 cu. in. (= 12.7 c. cm) liquid into the chamber, causing a motion of the chamber-piston of $\frac{0.775}{50.26} = 0.015$ in. The motion must

be provided for, almost entirely, by the unsupported ring of the diaphragm, the width of which may be so chosen as to provide for the required movement, because it may be very thin to resist the liquid pressure of a mercury-column 16 in. (40 cm) high. In addition to the intentional motion previously calculated, the effect of impact (shock) at instant of rupture of test-piece must be considered, as well as the circumstance that in the type Fig. 407 the chamber-piston is without a guide at the instant when the knife-edge of the scale-beam leaves its bearing on the tension-rod connected rigidly to the piston. An oblique load may at that instant be brought to bear on the chamber, which simultaneously with the impact strains the diaphragm unfavorably, and favors changes of conditions. It was only definitely ascertained in later types that these changes of conditions manifest themselves mainly as residuary phenomena, the magnitude and period of which depend upon a series of circumstances, and which are concealed by the frictional resistances in the small tubes. Both produce the effect that variations of load are not indicated at the instant of application, but only after an interval of time. It was easily demonstrable in this apparatus, Fig. 407, as the weight *G* consisted of several removable disks.

The residuary effects due to friction in pipes may be reduced to a very small amount if their length and diameter be so selected that but a slight excess of rise of mercury-column is required to force the necessary quantity of liquid through them in a small fraction of a second. Practicable dimensions can hardly be adopted in a construction as shown by Fig. 407 if the load is to be indicated within one second; this is, however, not necessary for all cases.* When using the type Fig. 407 it must be borne in mind that the quantity of mercury to be moved should not be too great, so that the inertia of the mass under rapid changes of load may not become effective,

* The use of spring-gauges would be more suitable for constructions of this kind.

which would again affect rapidity of indication. The easiest way of removing the evils just described would be to reduce the quantity of the liquid passing through the pipe to a minimum. This condition requires minimum motion of piston, thus at the same time reducing changes of condition of diaphragm to a minimum.

g. Types shown in Figs. 407 and 408 fulfil this requirement in so far as the working motion of the piston, i.e., the oscillations during adjustment, are reduced to a very small quantity. If an electric key *k*, Figs. 406 and 408 or Fig. 405, be used, which transmits the relative motion between piston and chamber to the finial on a magnified scale, using a very weak current, and a condenser if possible, it may be easily possible to reduce to a very small amount the motion of piston necessary to make contact. For a weak current a motion of 0.00078 in. (0.02 mm) suffices for making and breaking contact. If the above dimensions be used and the leverage of the key is $\frac{1}{50}$, the motion of the piston of chamber will be only $0.00078 \times 0.02 = 0.0000156$ in. = (0.00004 cm). Actually this motion will, however, be greater, for several reasons, because in the first place, due to inertia of masses, the separate motions will all pass beyond the zero positions, and secondly, elastic deformations of the chambers occur which produce variation of volume of chamber and unintentional motion of the electric key; there will, moreover, be differences in position of piston relatively to the chamber because of defective guiding of the former, and finally, due to sluggishness (lag) caused by the action of regulating devices (in Fig. 408 the pump, in Fig. 405 the clock and intermediate mechanism). It was found practically that in form 408, without materially changing the result, it was possible to reduce the multiplication to 1/1, or to attach the contacts directly to chamber and piston.* This shows that actual motion of the piston in the apparatus used may be safely estimated at 0.002 in. (= 0.005 cm), an amount which

* Note remarks in (*528, b*).

may perhaps be reduced in new designs when considering all of the circumstances previously discussed. If this be used as a basis of calculation it will be found that to produce a change of motion of the piston 0.0915 cu. in. of liquid must pass through the pipe, or 1/8.5 of that required in form *l*. In this case it will also be wise to shorten the pipe and to make it sufficiently large.*

This volume of liquid may still be reduced considerably by careful selection of all dimensions and adjustment of the devices, but it will always remain the essential difficulty, which, according to my present experience, may be met most satisfactorily by entirely shutting off the liquid in the chamber from the mercury-chamber. This has been successfully done in the latest apparatus for the 50-ton machine (machine *G* of the Testing Laboratory); the two diaphragms secured in the contact-chamber (Fig. 8, Pl. 5) seal the liquid within it. The mean ratio of area of these diaphragms and the support is $\frac{1}{880}$, and the maximum play of the diaphragms is 0.0312 in. (= 0.08 cm) limited by the sealing-screws, their area being 0.2 sq. in. (= 1.3 sq. cm). The total volume of liquid passing through the tube for each oscillation is, however, much less than $.0312 \times .2 = .00624$ cu. in. (= 0.104 c. cm), as here also a motion of the point of contact of but 0.00078 in. suffices to make contact. Assuming the play as tenfold, the motion of the piston will be about $10 \times \frac{.00078}{880} = 0.0000078$ in. = (0.00002 cm), and this is in fact very close to the actual motion of the piston, as all errors previously caused by different position of the key and defective guiding of the piston have been eliminated in the final form of apparatus.

k. It is no doubt of value and instructive to also discuss the failures caused by the two last-mentioned circumstances. It

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* Note that Emery uses pipes 0.048 to 0.058 in. in diameter, and that the pipes are sometimes made very long. An accurate investigation of this idea would be appropriate (*559*).

will be seen how frequently neglect of deformation of detail parts makes a problem more difficult.

At first I was of the opinion that no better guide could be provided for the piston than by rigidly connecting the column to it, which itself was guided by the link 57 attached to the cross-head, Figs. 1 and 3, Pl. 5, until my attention was accidentally called to the fact that this method of guiding was extremely questionable. The recording-drum was once operated by the clock 86, 87 attached to the left of it on the main column, for the purpose of determining the reliability of the clock, and intended to make minute-marks on the paper by means of the pencil 83 on the mercury-vessel. At the same time an assistant was making a tension-test on the machine, and although the lever 25 was not at all in contact with the column 56, the apparatus began to work in exactly the same manner as though set in operation intentionally; it recorded a diagram which was very similar to that obtained during a tension-test. This was caused by the fact that the pressure-column and the support followed the deformation of the testing-machine, thus causing changes of position of the piston relatively to the chamber, which set the key, then still in use, into action. At first no explanation was found for this phenomenon, until accident a few days later again succored us. A spirit-level used in the investigation of the causes of the phenomenon was lying beside the left-hand column 2 on the bed 1 of the machine, and plainly showed flexure during test. Further tests showed that the upper planed surface of the bed near the left-hand column was deflected 15 sec. in the axial plane of the machine under a load of 15 tons, while no change was shown by the level when placed beside the hydraulic cylinder at the centre. In a direction at R. A. to the first position of the level the deflection measured at the edge of the bed, on the central plane of column 2, was 6.3 sec. under a load of 15 tons; at the central plane of the cylinder 12.6 sec. under same load, and these deflections also had opposite inclinations.

After this experience the rigid connection of piston and pressure-column was discarded, that at present used adopted, and a guide for the piston was introduced. The electric key attached to the edge of the support was also discarded, and it was attempted to make it independent of the deformation of the piston, by using the relative motion of pressure-column and frame of calibrating weights. For this purpose a steel rod $5\frac{1}{4}$ in. long and 0.08 in. diam. was used to transmit the motion to the end of the key, which had a ratio of $\frac{1}{100}$. This rod was again a source of trouble. For as soon as an open door or window produced a current of air, the diagram became serrated, which did not represent the character of the material. The slightest thermal changes immediately affected this rod, and produced changes of position of equilibrium of the support-piston which caused changes in the height of the column in the mercury-vessel. Only when the electric key was made dependent upon the motion of the liquid in the pipes alone results quite satisfactory were obtained.

i. But the recognition of the fact that the volume of the liquid in motion is the essential condition of satisfactory action was the reason for pursuing the subject still further. Further attempts were made to reduce the motion by the principle shown by Fig. 409. In order to reduce the effective area of the mercurial contact-chamber to a minimum, and at the same time to remove the resistances to motion which the small diaphragms may still produce by unsymmetrical stress, they were replaced by a small rubber sack *c*, which seals a small glass globe *a* filled with mercury; the sack fits into the end of pipe *g* leading to the support. Under increasing pressure in *g* the mercury passes from *a* through an orifice of about 0.003 sq. in. section into the bulb *b*, forming a globule, and until it comes into contact with the platinum point *e*. *b* contains a non-conducting liquid, and hence the current is only closed upon making metallic contact. A second sack, *d*, seals the bulb *b* and the non-conducting liquid from the pipe *h* leading to the recorder.

Assuming the motion of the globule of mercury to be 0.02 in. (0.05 cm), the liquid to be displaced would amount to 0.00006 cu. in. (= 0.001 c. cm) and the corresponding motion of the piston to 0.00000039 in. (= 0.000001 cm). The motion of the test-piece supported by the scale-beam would be $\frac{1}{350}$ of this amount, if it were possible to produce an absolutely rigid machine-frame; actually elastic deformations of the frame must also be considered. If sudden greater variations of load occur, as at the instant of rupture, the clock is not able to follow them instantly and the small rubber sacks must absorb the excess of load and become check-valves; hence arises the case of the scale-beam, in which it comes to bear against the upper or lower stop, transmitting its remaining moment of force to the frame. This will produce a transfer of the liquid in the rubber sacks, which is estimated to amount to about 0.03 cu. in. (= 0.5 c. cm), corresponding to a motion of the piston of 0.000002 in. (= 0.000005 cm), representing the maximum play of the diaphragm; it would be equalized by an extension of the test-piece amounting to about 0.0000000078 in. (= 2 ten-millionths millimeters). Hence the bar would be released from all load by a very minute residuary extension when the test is interrupted by stoppage of the machine, if the elastic deformations of the machine, acting like a spring, did not strain it and necessitate greater motion to release all load.

It was precisely this exceedingly favorable application of load to the test-piece which enabled it to adjust its resistance to any speed of loading that induced me to adhere tenaciously to the realization of the fundamental principle adopted by me, and will be the cause of further study in the same direction, by searching for designs which will permit the work of deformation of machine-frames to be reduced to a minimum.*

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* I desire at this place to again repeat that it would be altogether wrong to use complicated designs for machines for routine work. The simplest is the best, and an accuracy of 1% suffices.

I desire to call attention to the cause which produces the irregular appearance of the curves recorded by the machine; it is the inaccuracy in the chains used to transmit the motion of the mercury-vessel. This always produces a serrated appearance of the diagrams, although the oscillations of the mercury-vessel about its position of equilibrium are so very small that their effect on the motion of the pencil can hardly be seen with the naked eye (see Fig. 410). These reasons were the cause for substituting for the clock a pump-cylinder, operated by the city water, the piston of which transmits its motion directly to the mercury-vessel. (This device gave but little satisfaction in service because of the impurities in the water.) At the same time it shall be attempted to dispense with the relay by using a duplex device like that shown by Fig. 409, and avoiding oscillations about the position of equilibrium, permitting the loading-device to come to rest as soon as the test-piece comes to rest. The character of this device is shown by Fig. 411; it will be readily understood if it is stated that the electromagnetic governor of the pump W comes into action only when metallic contact is made at k_1 and k_2; as soon as the contact is broken one or the other of springs F_1 or F_2 draws the valve S into its mean position, closing both ports, or at least opening them to a like degree. The play of the two keys k_1 and k_2 may be adjusted by means of the adjusting-device R in such manner that the slightest change of pressure will make or break contact.

k. As will be seen from the foregoing, there are several causes which produce slow variations in the internal resistances and the ratios of multiplication, and it was initially considered necessary to have a rapid and convenient means for calibrating the diagrams of the recorder. For this purpose the series of calibrating weights is used primarily, by which the record of load is invariably recorded on the paper both before and after test. The arrangement of the calibrating weights is the same as that of the main balance-weights. The value of loads

corresponding to length of ordinates recorded on the paper may also be determined at any time during test, by loading the right side of the machine by the balance-weights until the left hand knife-edges are just released from the pressure-column. The recorder returns to 0, and the weight on the right side indicates the value of the ordinate. Meanwhile the stress in the test-piece remains unchanged.

The present arrangement (as described under *e* and *g*) has answered admirably, except as to the slight defects noted in the investigation of resistance of heated iron; see (*L 1*, 1890, Part 4), in which the results found during calibration are also given. The small serrations produced by the irregularities of the clocks interfere but little, and still permit sufficiently accurate interpretation of values of ordinates. The ordinates are sufficiently proportional to loads.

By use of such automatic loading-devices it is ultimately possible to obtain the record at any desired point, and in fact close to the test-pieces in large machines, as the system may be modified in many ways. But in this case it should again be tried to use a spring-gauge to obtain simpler devices in order that the load-indicator may be placed in any desired position near the machine.

l. To complete the description of the machine at this time, two additional devices should be mentioned: a clock on the left column, originally used for automatically governing the piston speed, but which was found to be unnecessary and is now used occasionally to revolve the recording-drum uniformly; the additional devices are two Loewe heaters. Only the one on the right side is shown. They serve for heating the test-pieces in an oven suspended from the machine, Fig. 18, Pl. 5, when tests are to be made at high temperatures (*295–308*) (*L 1*, 1890, Part 4).

D. Designs of Machines for Various Kinds of Tests.

1. Nuernberg Stock Co., for Machine Construction; formerly Klett & Co., Nuernberg. (Pl. 3–5, *L 239*.)

564. In General. This concern builds the Werder and Martens types of testing-machines. The Werder machine has been introduced even outside of Germany; of the Martens machine but one has been built, for the Charlottenburg Testing Laboratory, although it has given satisfaction in every respect during fifteen years of constant use. The general details of these machines have been described in (*453*, *483*, *489*, *495* and *497*).

565. Design. The Werder machine is horizontal, arranged for tension, crushing, transverse, thrust, torsion, shearing and punching tests; it is generally built of 100 tons capacity, Pl. 3, and has become especially known through Bauschinger's numerous and important investigations. A smaller machine of slightly different construction is built by the Company like that shown on Pl. 4, Figs. 6–15. The large machine is driven by hydraulic power (*453*), the smaller by screw 20–26, Figs. 6–8, which can be regulated by hand by means of rods and levers 27–34. While the load-indicator is movable and at the same end as the power in the larger machine, the two act at opposite ends in the small machine and are bolted to the bed. The large machine is intended for long and large pieces (31 ft. in tension 24.6 ft. in thrust, and 11.5 ft. in transverse test); the small machine can test pieces 7.5 ft. in tension.

566. The Martens machine (*L 113*, *115*, *162*) has been so to say built as a special machine for the Charlottenburg Testing Laboratory. It serves almost entirely for tension-tests of round bars, especially for tests with instruments of precision for the determination of elastic properties, for tensional resistance of metals at different temperatures,

and because of its sensitiveness, for more delicate tests. As it has been found reliable and very constant in lever-ratios during the frequent calibrations and also under dead loads up to 11,000 lbs. (5000 kg), it is now used as the starting-point in all calibrations of the testing-machines at the Charlottenburg Laboratory. The different details have been described in (*508, 523, 524, 530, 546, 563*). It may be again emphasized that the machine was so designed as to be operated and controlled by a single observer from his position behind the reading-telescopes, a principle which is embodied in all the machines at the Laboratory except the Werder. An assistant is required, as in every case, only for adjusting the mirror apparatus to zero reading.

567. Tension-test. The devices used with these machines for tension-test are known from their descriptions in (*67–72*). The numerous devices used by Bauschinger in the Werder machine are described in his "Mittheilungen" (*L 2*). Tetmajer also described many devices (*L 3*). Attention may be called to Pl. 5, Figs. 12–17, which show the holders of the Martens machine. Figs. 15 and 16 illustrate the holders for copper flat-bars, etc., which require less than 20,000 lbs. max. load. It consists of serrated liners, fitted in spherical bearings in the sliding wedges. A similar shackle is used by Riehlé, Pl. 19, Fig. 25. The serrated liners can adjust themselves neatly to the cheeks of the test-pieces, and are arranged so that both wedges must advance simultaneously (*72*). Fig. 14, Pl. 5, shows holders for tension-test pieces $\frac{3}{4} \times \frac{3}{4}$ in. section, for determination of factors of elasticity of mortar and concrete. Fig. 17 shows holders for determination of adhesion of glue and similar materials. The two blocks of wood glued together crosswise of each other are provided with iron plates at their inner ends, one having a conical cavity, the other a groove, into which the spherical bearing-ends of the claws fit neatly without constraint, one in the

cavity, the other in the groove. As these depressions are made to a jig, the direction of stress must pass very nearly through the centre of the layer of glue. After each test the glued surfaces are planed off, thus always using fresh surfaces; they are glued in a special device under a dead load, and hence without joiners' clamps.

568. Crushing- and thrust-tests. The platens for crushing-tests have been indicated in (*73*), and for the large 100-ton machine are illustrated on Pl. 3, Figs. 13–17. (*L 1*, *2* and *3* describe further detail, especially for thrust-tests.) Figs. 15 and 16 illustrate the centring devices designed by Bauschinger; Fig. 18 shows the mirror apparatus attached to a crushing-cube. The holders for the 50-ton machine are shown on Pl. 4, Figs. 10–12.

As the driving-mechanism and load-indicator act directly on the test-piece, the application of load must be indirect in the crushing-test, because of the necessity of completing the cycle of forces, as is done in all machines constructed on the same principle, see Fig. 412. The construction will be understood from Figs. 10–12. In the thrust-test the Werder machine is arranged as shown by Figs. 8–12. The tension forces of the machine are transmitted to the test-piece by the cross-head 23, rods 59, and scale 41, 42, thence to the bearing 43, 44, braced from the frame of machine. Measurements are made as stated in (*190–198*).

569. Transverse Tests. The Werder 100-ton machine is no doubt more suitably equipped for transverse test than any other German machine. The arrangement is shown by Figs. 23–25, Pl. 3. To make transverse tests the heavy cast-iron girder 46, 13 ft. long, supported by girder 38, is braced against the bed 5; it serves to support the test-piece 51, the supports of which may be spread 11.5 ft. Rollers 50, carried on supports 49, adjustably mounted on the graduated girder, provide proper bearings at desired distances.

... may be desired ... is built by ... shown in ... this device can ... mechanical belt transmission is

... straight and crossed belts from shaft 17 by ... 14 ... 13, 12, 11 to the test-piece 8, which ... other end to the bracket 5, supported on knife edges. This bracket transmits the force of the torsional

moment to the scale. This device is much superior to that first described, because the sources of error are materially reduced by the independent drive, and especially by support of the bracket 5. The bracket 5 does not shift its position noticeably, while it must describe a large arc in the other design before the whole device can be reversed so that the pawls in wheel 57, Pl. 3, Fig. 28, may be changed. This necessitates frequent interruption of the test, while it may be continued at will with the device shown on Pl. 4.

572. Shearing and Punching Tests. Werder's arrangement for shearing and punching is shown in Pl. 3, Figs. 19–22. The shear-blades and punches are secured to the blocks 83 and 84, the latter bearing against the beam 46 used for transverse tests, while 83 is pressed against the test-piece by means of the carriage 45 and the rods 17.

573. Tests of large buckle-plates, ceilings, arches, girders, and all kinds of spreading details of constructions and of machines may be tested by the Werder machine after removal of the girders 38, Figs. 1 and 2, Pl. 3. Dimensions may be of any limit if a pit be provided in the floor during erection. Proper abutments must of course be provided, which should bear against the frame 5 of the machine.

As will be seen, the Werder machine is very convenient for tests under most manifold conditions, and this, in addition to the pre-eminent merit of Bauschinger, was the principal reason why it was so highly praised and largely introduced in spite of many inconvenient points.

2. Mannheim Machine Works, Mohr & Federhaff, in Mannheim. (Pl. 6 and 7.) (*L 27*, 1882, p. 545; *12*, 1884, p. 141.)

574. *In General.* The Mannheim Machine Works make a specialty of building testing-machines of all types and for all purposes, as will become manifest from Pl. 7 and the appended explanations. It will not be necessary to give a

detailed description of the tension-machines additional to the many details given in (*72, 376, 479, 492, 493, 517*).

575. The machines are vertical, operated by mechanism or by hydraulic pressure, by hand or by power. Loads are almost invariably measured by the beam-scale.

576. Tension-test. The holders for tension-test have been previously described in (*67–73*). Special attention is called to the devices shown on Pl. 6, Figs. 11–20. Two or three liners are first placed in the cylindrical recesses in the holders, which take the wedges. In this manner the gripping-wedges, by turning in the cylinder, may adjust themselves to the surfaces of test-pieces when they are not parallel. The wedges are compelled to advance simultaneously, being connected by pins. In tension-holders for wire rope they take the shape of the Baumann socket. The gripping surfaces of these wedges are poured with a soft alloy.* Bauschinger, Kirsch, Tetmajer, and others used similar alloys for their clamps.

577. Crushing-test. The devices for crushing-test are as in scheme Fig. 412; they are illustrated on Pl. 6, Figs. 5–8.

578. Transverse Test. The tension-machines are equipped with devices for transverse loading based on the scheme of Fig. 413, which are not here shown in detail, but can be seen in the catalogues of the firm. Pl. 7, however, shows a few special machines for transverse tests of cast iron, Fig. 8, of springs, Fig. 2, and of rails, Fig. 6.

a. The machine shown by Fig. 8, Pl. 7, for testing cast iron is based on the principles shown in Fig. 414. The scale 4, 5 is built in a frame, which is raised by screw-gearing

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* The Charlottenburg Testing Laboratory uses the following alloys for its Baumann rope-sockets:

a) 50 Sn+50 Pb melting-point 250° C.;—S_M = 380 at. and S_S=350 at.
b) 41 Sn+41 Pb+18 Sb " 260° C.; " =1150 at. " " =640 at.
c) 36.5 Sn+36.5 Pb+27 Sb " 200° C.; " =1250 at. " " =570 at.

6, 7, while the scale is kept in balance by shifting the poise. Loads are indicated by the poise to 0.2 lbs. (0.1 kg); maximum loads are from 1300 to 2200 lbs. (600 to 1000 kg); bearings may be shifted to from 23 and to 40 in. (580 and 1000 mm). Deflections may be read to $\frac{1}{250}$ in. (0.1 mm) by the indicator 8, 9, Fig. 414, the scale being adjustable, so that the initial reading may be made at 0.

b. The machine shown by Fig. 2, Pl. 7, is used for testing leaf and spiral springs. It is operated by hydraulic pressure or by screw, and provided with a decimal scale, and so arranged that the loaded spring may be subjected to vibrations. The spring may be supported by links so that the ends are free as in actual service. Deflections of the springs are indicated by a pointer on the frame. The machines are built of various capacities up to 35,000 lbs. (16,000 kg) for lengths of springs up to 98 in. (2500 mm).

c. Rail-bending machines are built according to Fig. 6 up to 83 tons (80,000 kg) capacity. Distance between supports is variable between $19\frac{1}{2}$ and 39 in. (500 and 1000 mm). They are driven by hydraulic pressure, and, as in case of other machines built by the firm, may be operated by hand or by power, or as shown by Fig. 6 by an intensifier.

579. Shearing-tests are made as shown by Figs. 9 and 10, Pl. 6, by inserting the steel rings 216, Fig. 161, in the jaws, thus shearing the test-piece.

580. The Mannheim Machine Shops builds devices as in Figs. 9, 10 and 11 for bending and folding tests, some of which are partly driven by hand and some by belts. By machines built as in Fig. 20, flat bars of $2 \times \frac{5}{8}$ in. may not only be bent about definite radii, but they may also be doubled up. Machines as per Fig. 11 may test flat bars of 2×1 in. section.

581. Torsion-test. Fig. 12 shows a machine for torsion-tests of wire, up to 0.27 in. (7 mm) diam., while at

the same time subjected to tension. The number of revolutions is indicated by a counter.

582. Devices for bending-tests of wire (*394*) machines for testing chains, couplings, etc., are also made by the firm. A strong beam may be attached to the holders for the purpose of calibration by means of standard weights placed on scale-pans suspended from the beam.

3. Alsatian Machine Co., Grafenstaden.

(Pl. 8.) (*L 12*, 1882, p. 8.)

583. In General. Machines are built in three sizes, of 25 and 50 tons (25,000 and 50,000 kg) capacity, according to Figs. 10 and 3, Pl. 8, driven by screw-power, and of 100 tons (100,000 kg) capacity, driven by hydraulic power. The load-indicators of the first machines are built according to the scheme Fig. 348 (*492*); the scheme of the 100-ton machine is shown by Fig. 415. Scales are provided for calibration.

584. The large 100-ton machine is built since the sixties mainly as a transverse-test machine, on the design of Marié, but is also provided with devices for tension and crushing test. By means of a knife-edge the piston 2 acts on the test-piece 3, supported on bearings, the resistance of which is transferred to the cross-head 4, and by means of rods 5 to the scale, which is duplex; it consists of pairs of levers 6 and 7, which act on the common poise-beam 8. Crushing-tests are made between piston 2 and the cross-head 4. For tension-tests the frame 10, composed of 4 struts, is lowered onto the table of the piston 2; the loads are then transmitted through 10 by way of 4 to the scale.

585. Tension-test. The devices for this need no explanation, and are shown by Figs. 11–20.

Those for crushing-test are designed on principles shown by Fig. 412 and Figs. 4 and 5, Pl. 8.

586. Transverse Test. Machines built as shown in Figs. 3 and 10 are arranged for transverse test as shown by

Fig. 413, and for the 50-ton machine as shown by Figs. 6 and 7, Pl. 8.

The bearing between supports in the latter is $39\frac{1}{4}$ in. (= 1 m), while it is variable in the similarly constructed devices for the 25-ton machine from 8 in. to $39\frac{1}{4}$ in.

4. Machine Shops of Heinrich Ehrhardt in Zella, St. Blasii.

(Pl. 9.) (*L 229.*)

587. In General. The Ehrhardt shops build the Pohlmeyer machines in three sizes, 25, 50, and 100 tons. The machine and the Martens load-indicator are described in all their details and capabilities in (*523, 534 a–e, 465, 493,* and *533*) so completely that they require but few more words. The machines have been so greatly perfected during their many years' service in the Charlottenburg Testing Laboratory that in their present condition they may be fully recommended for practical use, because they are very convenient and readily controlled at all points during use. They require, however, **like every other testing-machine,** an initial and occasional calibrations for accuracy. During the first calibration the position of the support 23, Fig. 2, should be clearly indicated on the base-plate by a scribed line, plainly visible, in order to show any variation immediately. The rapid proof of accuracy of the machine up to loads of 10 tons within practical requirements can be easily obtained at any time by means of the control-balance provided with each machine. The more accurate investigation is made in a much more tedious manner by means of standard bars (*534, f*), as long as better means have not been found.

588. Tension- and Crushing-test. The holders as built by Ehrhardt are shown by Figs. 1 and 2, Pl. 9; those used by the Testing Laboratory are shown in scheme by Fig. 33 (*71*). For rounds a slide as in Fig. 416 is inserted in the holders in place of the two serrated wedges, having a slot and a spherical seat for the corresponding bear-

ings. The simple devices for crushing-test, the lower one with spherical seat, are drawn in Figs. 5–8, Pl. 9. For bodies of larger dimensions larger plates are placed over 29 and 30 to increase the bearing-surfaces.

589. Transverse Test. For this test supports 33 and 35, with a long right and left screw to adjust their distances [which may be $39\frac{1}{4}$ in. (1 m)], are attached to the table 4, Figs. 1, 2 and 16. The bearings resting on these supports should be semi-cylindrical and loose, as shown in Fig. 18, in order that they can be used in case of test-pieces in wind.

590. Shearing- and Punching-tests. The devices for these tests designed by myself have been illustrated in Figs. 161 and 168 (*216* and *222*.)

5. Machine Shops of C. Hoppe, Berlin.

(Pl. 10.)

591. In General. But one of the 500-ton Hoppe machines has thus far been built, and that for the Charlottenburg Testing Laboratory. It is long enough for tension-test pieces 55 ft. 9 in. and thrust-tests 49 ft. $2\frac{1}{4}$ in. (17 and 15 m). The general arrangement is shown by Fig. 417, in which individual parts are numbered as in Pl. 10, also by Fig. 417*a*.

592. It is operated by a movable hydraulic press, the cylinder 2 being held in the casting 3, which, with the tension-rods and the casting 4, forms the carriage. The latter runs on wheels 8 on the bed-plate 1, which forms its track and consists of two strong cast-iron lattice girders, which are braced by similar horizontal girders and are also built into the masonry foundation. The piston 6 is connected to cross-head 7, through which and the casting 3 pass the main straining-spindles 13. These spindles have a screw-thread for about 40 ft. (= 12 m) which permits adjusting the position of cylinder or piston to any desired point.

a. This adjustment is made in case of tension-tests by causing the nuts 9 to bear against the cross-head 7 on the piston 6, as shown in Figs. 1–3. The uniform adjustment of both nuts is secured by bevel-gearing. If pressure be admitted to the cylinder, the latter with the carriage is forced to the right, and the test-piece held by 4 is subjected to tension, while the main spindles 13 are subject to thrust. The scale completes the balance of forces between spindles and test-piece at the other end of the machine.

b. For thrust- or crushing-tests the first pair of nuts, 9, is adjusted to free the piston, while the second bears against the cross-head 3 of the carriage, the cylinder thus being fixed to the spindles 13. The pressure will advance the piston, producing thrust in the test-piece, while the spindles are subjected to tensile stress. Equilibrium between both forces is again secured by means of the scale. To transmit the thrust of the piston to the test-piece and scale, a prolongation is provided on the piston which passes through the cross-head 4 and carries the platen at its front end (spherical bearing as in Fig. 38).

c. Short Test-pieces, such as stone, masonry piers, etc., may be tested directly between the two cross-heads 4 and 7 without use of the scale. The use of the scale may be omitted because very exhaustive series of tests have determined the relation between the hydraulic pressure in the cylinder and the loads indicated by the scale (*595, i*), and each test made by use of the scale increases the certainty of the empirical factor of effective hydraulic pressure.

593. As the long spindles are subject to thrust in tension-tests, it was necessary to brace them mutually by struts 31–33, and to connect them with the bed of the machine. The strut 32 is movable, so that rods 10 can slide it along as the press advances, but is returned to its original position when the press moves back.

594. The bed of the machine absorbs none of the forces

transmitted by the test-pieces, and only that stress in the spindles 13 produced by flexure, and otherwise merely serves to support the weight of the machine. The wheels of the carriage are supported by springs, which may be so adjusted that all load is carried by three of the wheels, and the guides in the cross-heads 3 and 7 serve only to steady the motion.

595. The principles of construction of the load-indicator are shown by Fig. 417. Tensile or crushing force in the test-piece always tends to approach the heavy cast blocks 16 and 19 toward each other by the reaction to the tension or thrust in the spindles 13, and this tendency is counteracted by the scale, at the same time measuring the active forces. This is done as follows:

a. In tension-tests the tension produced by 4 in the body is transmitted to cross-head 19. On the latter, however, the four cast-iron angle-levers 40 are supported in bearings. The knife-edges at the short lever-arm act on the struts 17, which bear by knife-edges on the cross-head 16. The latter transmits the forces applied by 17 by means of the nuts 15 to the spindles 13. The circuit of forces is then closed by the hydraulic pressure in the press, as previously stated. The force transmitted to levers 40 tends to spread the long arms of the two angle-levers. This tendency is counteracted by the ties 23, which act on the scale-beam 25 supported by the two upper levers. The moments produced in the angle-levers are also transmitted to the lever 25, common to both angle-levers, and thence to the travelling poise-scale 35. The entire load-indicator is movably mounted on a series of rockers, still to be described; these rockers transmit the entire weight to the bed of the machine. The load-indicator is maintained in its position horizontally by the block 14 rigidly connected to the bed, and holding the main spindles 13. The spindles 13 are, however, not fixed rigidly to the block 14, but are cushioned by rubber buffers, which counteract the inertia of masses at the instant of rupture.

b. In the thrust-test the force is transmitted from 6 by means of the test-piece to the cross-head 16, thence by struts 17 and angle-levers 40 to cross-head 19, which transmit it to the spindles 13 as tension to balance the press. The action of the scale is then the same as in the tension-test.

c. The following may be added about the details of the load-indicator. It is supported on eight rockers, 26, 27, 28 and 30, which are attached to both sides of the machine. The rockers 26 and 27 support the cross-head 19, which for this purpose is connected to each side of the machine by stout struts 34 by serrations and bolts. The rockers each consist of one strut to transmit the dead weight of the parts of the machine to the bed. These rockers rest at either end on knife-edges in bearings. They are, however, at the same time surrounded by straps which, bearing on knife-edges, prevent lifting of the parts of the machine from the bed. The cross-head may therefore move freely in the direction of the axis of the machine, but vertical motion is prevented by the rockers and straps. Tilting of cross-head 19 is also prevented in case unequal transmission of loads to the scale should produce this tendency. The cross-head 16 is similarly connected to the bed. The stout bars 29 form a stiff triangle with 16, supported by 28 and 30. The spindles 13 pass loosely and frictionless through the chambers at the right-hand end of the triangle.

d. It will be seen that the two cross-heads are free to move axially to the machine, and constantly act against each other by the forces transmitted in opposite directions by the test-piece and the main spindles. When not in service the two cross-heads 16 and 19 are held in position on the spindles by the nuts 15 and 20, and therefore cannot tip, although in unstable equilibrium, because prevented by the block 14. The friction in struts 31–33 also assists in this respect.

e. As the loads are transmitted from cross-head to cross-head by four braces, special attention was given to certainty of uniform transmission. The knife-edges in the braces neces-

sarily became long if the stress mentioned in (*493*) was not to be exceeded. It is not easy to obtain perfect parallelism in all of the eight lines of contact (edges and bearings), and small errors must be expected. Therefore the knife-edges were fixed in slotted castings as shown in Fig. 418, which allowed them to take a perfect bearing along their entire edges by very slight elastic deformation, thus eliminating the ever-present slight errors.

f. The cast-iron levers 40 must undergo elastic deformations when supporting the loads they are intended to bear. If they be then considered as bending about the knife-edge assumed to be fixed, there will be a point in the long lever-arm which will remain quite or nearly in its original position, while the stress varies from 0 to the maximum and produces increasing deformation. At this point the designer has located the strut 22 for the lower lever. This point may be found by calculation or by trial. The Testing Laboratory located it in this manner by applying mirror apparatus at both struts 22, and determined their elastic deformations. The struts were then shifted in the axial direction of the machine until the elastic deformations became a minimum under maximum and under zero loads. The struts were then definitely fixed in this position.

g. The dead weight of the angle-levers 40 and of other parts of the weighing-machine produced an effect especially under small loads of the scale, because it produces an initial stress in the upper struts 17, while the stress is diminished in the lower struts. Therefore the dead weight of the parts of the machine had to be transmitted to the bed of the machine. This was done by the resilient strut 42 and balance-lever 43, as shown by Figs. 417, 419, also 417a.

h. In order to take the impact coming upon the scale at each rupture of a test-piece, a wooden buffer 45 is placed between each pair of angle-levers and attached to struts 44.

So as to be able to determine the lever-ratios of the scale, the designer provided a calibrating-scale 21, Figs. 1 and 2.

i. These check-balances are rarely reliable and can only be used for calibrating the machine under very small loads. Every careful calibration of a machine proves that this is insufficient. The Testing Laboratory therefore dropped the use of a check-balance from the beginning and replaced it by a connecting-rod called into use when testing short pieces, of such shape and dimensions that it could be used as a standard bar for calibrating the machine. It is cylindrical, of 6.3 in. (160 mm) diam. and 27.25 ft. (8.4 m) in length, made of Krupp gun-steel, and was provided with an additional connecting-rod, as shown by Fig. 420, of the same material. This additional rod was to serve to prove the resistance of the machine to impact at the instant of rupture. It was also used at the same time to determine the material of the standard bar accurately, so as to obtain a comparison with the other machines of the Laboratory. For this purpose the elastic behavior of the additional rod was carefully determined up to loads of 110 tons (100,000 kg) in the Werder machine, which was carefully calibrated and adjusted before and after the test. It was then coupled to the connecting-rod of the Hoppe machine, and then strained so that the same several mirror apparatus used in the Werder machine again gave the same readings as before. For each load thus determined simultaneous readings were taken on the mirror apparatus attached to the large connecting-rod of the machine (*696*), on the scale, and on the gauges.

By a number of complete series of observations it was thus found that the extensions of the different parts of the additional rod and of the large standard bar were proportional up to 110 tons (100,000 kg) load, while the scale showed insignificant regular variations. The several mirror apparatus were then removed and the first section of the bar was ruptured under a load of 220 tons (200,000 kg). The test was made by setting the poise on the scale to a certain load, and attaching an electric key to the beam, then admitting pressure to the cylinder by means of a valve located in an adjoining room, until the beam, brought to a balance, touched the electric key and started a bell. After a slight release the poise was set at a greater load and the test thus continued until rupture occurred. Thereupon the sections intended to fail under loads of 330, 440 and 550 tons were ruptured in a similar manner, and the fact determined that the machine successfully withstands such shock and impact.

Since then the relation between the readings of the scales, the gauges (*592, c*) and the elastic extensions of the large standard bar have been determined by frequently repeated tests. It was found that the scale-readings are not strictly proportional to the extensions of the standard bar. Plotting them gave a slightly

curved line. As experience at the Testing Laboratory has shown that scales suffer changes more readily than standard bars, the large standard bar shall in future be used as the standard for all calibrations of machines, and corrections for scale-readings will be tabulated on the basis of repeated tests with the standard bar.

596. The Hoppe power-pump described in (*457*) is used for driving the machine; a pressure of 420 at. is required. A spring safely-valve 36 is provided on the high-pressure pipe beside the admission-valve 37 on the city main, for regulating the pressure; the spring-pressure on the safety-valve may be regulated by a scale which is divided in tons of load transmitted to the test-piece. Hence there can be no greater pressure in the cylinder than that allowed by the safety-valve. The observer controls all operations of the machine personally from his seat beside the valves. He need not leave his chair in front of the mirror apparatus (*696*), and is able to adjust the mirrors to zero from that position personally, operate the valves and scale, and read the latter by telescope and reflecting prism.

The water under pressure is admitted to the cylinder by valves 36 by means of telescopic tubes. Stop- and regulating-valves for cylinder 2 and return-cylinders 5 are located in front of the cylinder. The return-cylinder pulls the piston 6 back by means of chains.

597. Holding-devices are provided for tension-tests of rounds and flats of large dimensions, for 5-in. angles, for wire rope, and drive-ropes of 4 in. diam. and more, of heavy anchor-chains, etc. For tests of structural members the devices will be provided as required. Such devices should not exceed 32 in. in diam.

6. H. Gollner's Machine. (Pl. 13.) (*L 220.*)

598. In General. The Gollner machine has been built by the firm of F. J. Mueller of Prague since 1877. It is arranged for all kinds of tests. I can here describe only its

principles; Gollner described it in detail in (*L 220*). It is built for tension-tests with capacity of 20 tons, and for transverse and torsion tests with a capacity of 10 tons. But it is possible to disconnect the large lever, and it can then be used with one lever for tension-tests up to 2 tons for wire, leather, belts, wood, cement, etc., after attaching a small loading-device. The details of the machine have been described in (*452 479, 490, 492, 493*).

599. The scheme of the machine is shown by Fig. 421. It is operated by hand, either by the pump 15–17, Pl. 13, Figs. 1–5, or by screw-gearing 8–12. The press 5 is carried on the nut 8. The screw 13 envelops the piston 7 of the press and is guided in the machine-frame 3 by the cross-head 14.

600. The load-indicator, previously described in (*483, 490, 493*), consists of the levers 33, 43, and is provided with a poise-weight and balance-weight 46–55 deposited mechanically. The main lever, 33, may occupy two positions, the upper and the lower.

In the first case the pressure acts at the centre fulcrum upwardly. The machine may then be used for all kinds of tests; it is mainly used, with this position of levers, for tension- and torsion-tests. The upward tension in the test-piece is applied directly, but in crushing-test, as in Fig. 412 (*568*), indirectly by means of the device shown by Figs. 11 and 12, Pl. 13. The rods 35 are subject to tension-stress.

In the second case all forces acting on the lever are reversed; the machine is in this position especially suited for crushing, transverse and shearing tests. The force in crushing tests is transmitted by two struts 60, Figs. 4 and 10, braced between the fulcra 28 of the main lever and the carriage 19, counterbalanced by weights 20 and 21. The frame 25 of the scale is used as a strut between the fulcra 41 and 42 of the two levers.

The correct adjustment for one or the other condition of the machine is facilitated by + and − signs for the main

lever and the mark on the pump-lever 17; the main lever 33 can be secured in its correct position for + or — by the use of blocking-wedges.

601. The machine is operated for torsion-tests, as shown by Figs. 5 and 6.

The arrangement for transverse tests is shown by Fig. 4.

7. J. Amsler-Laffon & Son Machines, Schaffhausen, Switzerland. Pl. 14. (*L 3.*)

602. In General. The firm has made the construction of testing-machines one of its principal pursuits. It builds machines of great variety and capacity, excellently constructed.

As the peculiarities of the construction of driving mechanism (*406 a* and *447*), load-indicator, and mercury-gauge (*553*, *561* and *561 a*) have been fully described, a rapid review of the types shown on Pl. 14 and description of individual constructions shall suffice.

603 *a*. The simplest form of the Amsler-Laffon machine is shown by Figs. 1, 3 and 9 in those used for crushing-tests, built, as stated by them, after consultations with Prof. L. de Tetmajer. Operation and load-indication hydraulic, combined at the same end of the machine, sometimes set up independently of the machine (Fig. 9, also Fig. 6), loads applied to test-piece directly. The machine itself can hardly be simpler in design and arrangement than in the 150-ton type, Fig. 9. If the plungers in the press and the reducer actually run without friction, it must be admitted that no objection can be raised against the reliability of the machine. The plungers are so long, and they and the cylinders may be so easily and correctly fitted as designed, that oblique action (tilting) need not be feared. There are no packings which might suffer under the effect of shock at rupture of brittle bodies. All depends upon the question whether it is certain

that friction will always remain a sufficient minimum and invariably uniform. Therefore great care must be had to keep all dust or fragments of crushed material from the surface of the plunger-rods. To prevent this tin casings, cotton rings, etc., are used. It will be necessary to see to it that sufficient oil is always in the cylinders, and that it always leaks during test very slowly. The firm should not build any additional machines unprovided with devices which will at all times show the depth of liquid in each vessel, or the position of the movable plungers.

b. Like all other testing-machines, that of Amsler-Laffon requires periodic calibration. Unfortunately this calibration is not as easily made as in other machines; the check-balance or direct loading are only applicable within small limits, and are more or less unreliable. The use of standard bars and mirror apparatus is inconvenient because of the leaking oil, because it is not possible to maintain a definite load, and it is generally necessary to take readings during motion. This requires several expert observers, and is connected with greater uncertainties than is the case in machines which permit maintenance of definite loads.

The Charlottenburg Testing Laboratory has made a series of calibrations of a 30-ton crushing-press. I hereafter publish some of the results as an example, but will add that the investigations shall be perfected and carried on still further; the results do not thus far permit a definite opinion on the correct limits of error of the machine. In one series of tests the press was very accurately levelled, and a long beam placed across the spherical bearing used for crushing-tests, which carried the dead weight at either end. This was loaded so as to produce as nearly as possible a symmetrical load on the plunger. Two supports were provided for this beam, beside and independent of the machine, from which the rising plunger lifted the load, or which received it when descending. It was therefore possible to release the load com-

pletely, and as often as desired, at all stages of the test. The readings of the gauges were then compared with the weighed loads, and under ascending as well as descending plunger, as well as while the latter was rotating or at rest. In addition the agitator for rotating the intermediate plunger was either operated by hand, or by the machine in the usual manner, or it was left quiescent. The means of the observations are given in Table 42, which will explain itself.

Table 42.—**Calibration of the 80-ton Amsler Machine No. 51 by Dead Weight.**

The readings are averages: the small numbers represent estimations (hundreths of scale-divisions).

	Readings on Scale in kg (divisions = 0.1 tons).				
Series	1	2	3	4	5
Loads in kg.	Ascending Plunger; Agitator at Rest.	Agitator at Rest.	Descending Plunger; Agitator at Rest.	Plunger at Rest; Agitator Operated by Hand.	Ascending; Agitator Running.
1062	10 45	10 45	10 54	10 67	10 70
2051	20 38	20 37	20 52	20 61	20 75
2797	27 92	27 93	28 09	28 14	28 35
at	Probable error of reading $r = \pm$				
1062	7.2	7.8	3.2	5.5	9.6
2051	4.3	4.0	7.4	7.4	3.0
2797	12.0	12.2	8.6	5.2	5.6
	For ΔP = 1000 kg there will be units of scale:				
0 — 1062	984	984	992	1005	1008
0 — 2051	994	993	1001	1005	1012
0 = 2797	991	991	1004	1006	1014
Mean	990	989	999	1005	1014

In order to obtain a general idea of the degree of reliability of the observations, I have also added the probable errors as derived from individual readings; they vary from $\pm$ 3 to $\pm$ 12 kg. It may therefore be expected that errors beyond the amount of 30 kg (66 lbs.), or 1%, would be rare in this particular machine in its condition when tested, and under loads of 3000 kg (6 tons). The comparison of the different series of tests at once shows the great influence of the action of the agitator. The probable errors are slightly greater on an average in the first three series than in series 4 and 5. Table 43 is deduced from the calibration by means of the standard bar.

As soon as the new devices for calibrating standard bars and mirror apparatus, by use of dead weight, are available, the calibrations of machines shall be still more perfected and executed in greater detail.

c. The crushing-machines are converted into transverse machines in the simplest manner, as shown by Fig. 1. The two side supports can revolve about the cylindrical bearing-bar in this machine of small capacity (tests of tiles, cement slabs, etc., up to 2 tons resistance), so that they may be made to fit surfaces in wind. The central pressure-block is fixed and may be adjusted by means of screws before test. For larger forces (up to 5 tons) the machine Fig. 12 is used, which is also arranged for tests of standard cast-iron test-bars ($40'' \times 1.17'' \times 1.17'' = 100 \times 3 \times 3$ cm). In this case the end supports are again arranged so that they can adjust themselves to surfaces in wind (see Figs. 477 and 478). The machine is provided with a recorder, in which the card moves with the cross-head (deflection = natural scale), while the pencil moves normally to this direction, moved by the rotation of the float roller on the mercury-gauge.

604. The tension-machines must be built on the principle of applying load indirectly used by Amsler-Laffon, and are therefore not as simple as the crushing-

Table 43.—**Calibration of the 30-ton Amsler Machine No. 51 by Standard Bars.**

The unit of shortening of the standard bar for 1000-kg load was determined as = 63.2.

	To readings at *n* of the scale of the Amsler machine, at:															
	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	0
	corresponds to a shortening of the standard bar *n* . 63.2 units (1/200000 cm).															
	0	126.4	252.8	379.2	505.6	632.0	758.4	884.8	1011.2	1137.6	1264.0	1390.4	1516.8	1643.2	1769.6	0
	0	126	239	371	502	630	752	879	1002	1137	1259	1394	1508	1638	1779	0
	0	122	246	369	496	625	752	890	1002	1139	1260	1390	1517	1634	1768	—
	0	122	248	376	501	629	762	888	1014	1138	1262	1387	1521	1645	1773	0
	0	124	247	378	504	627	749	879	1015	1135	1270	1390	1511	1648	1773	+ 3
Mean	0	123.5	245.0	373.5	500.8	627.8	753.5	884.0	1008.3	1137.3	1262.8	1390.3	1514.3	1641.3	1773.3	+ 1
Variation from unit value	—	− 2.9	− 7.8	− 5.7	− 4.8	− 4.5	− 7.4	− 0.8	− 2.9	− 0.3	− 1.2	− 0.1	− 2.5	− 1.9	+ 4.7	—

Probable error of reading of all observations $r = \pm 2.5$ units or $\frac{2.5}{63.2} \cdot 1000 = \pm 40$ kg = 88 lbs.

machines. Different types are shown by Figs. 4, 5 and 6. The machine Fig. 5, of 25 tons capacity, is provided with a special screw-power; the hydraulic cylinder, therefore, functions essentially as an hydraulic support. It is arranged at the head, and the upper holder is suspended from it by a frame. The lower holder is guided by the side columns, and is provided with bevel-gearing, Fig. 20, by which it can be adjusted to a suitable height for length of test-piece before test. All the holders will be described together later on. The drawing shows the Amsler-Laffon recorder (*719*) attached to the left column.

a. The 50-ton machine is shown by Fig. 6 with an arrangement for transverse and crushing tests. The separate screw-power is wanting; the adjusting-screw is retained. The lower cross-head of the tension-frame is adapted for transverse tests, and is therefore connected to the upper cross-head with two additional straps. Crushing-tests are made under the lower cross-head and the head of the press. The holders shall be described later on.

605. Fig. 2 represents a machine, built according to the designs of Prof. C. v. Bach, for the purpose of making tension-torsion-(simultaneous) tests (*L 223*). The illustration no longer shows the machine in its final form in detail as built at present. It is constructed for torsional moments of 15,000 cm-kg. (= 1075 ft.-lbs.). The scheme of the machine is shown by Fig. 422. The screw-power 3 applies the tension to the test-piece *s* by means of the cross-head 5. Tension is thence transmitted through cross-head 7 and rods 8 to the piston 3, and measured in cylinder 10 by a mercury-gauge such as described in (*561*, *561a*). The bevel-gears serve for rapid adjustment of the cross-head 5 to thelength of test-piece; it is fixed by a dowel-pin. The torsional moment is produced by the worm-gear 6 mounted on the cross-head 5; it is transmitted by test-piece *s* to the cross-head 7, and its forces are measured

by mercury-gauges in the usual manner in the two cylinders 11 attached to the machine-frame.

Details will be found in Figs. 423 and 424 and on Pl. 14, Fig. 2.

606. Another small machine which serves for torsion-tests of wire under simultaneous tension is shown in Fig. 10 (*L 3*, 1890, Part 4, p. 238). It is driven by a crown wheel and pinion. The torsional moment is measured by two revolving grooved spiral disks around which two weighted springs pass; the leverage increases proportionately to the revolution of the disks, while the force remains constant. The recording-drum is mounted on the disk-axis, on which the torsional moment for each revolution is recorded. The number of revolutions is also indicated by a counter. The tension applied to the wire may be as high as 220 lbs. (100 kgs). The firm constructs a simple little machine for winding-tests of rope and telegraph-wire.

607. Fig. 13 illustrates a 70-ton (70,000-kg) bending-press for bending-tests (folding-tests, *372–392*), in which the span and interchangeable studs are variable. The span can be changed from 0.8 in. to 3.6 in. (2–9 cm) by wedge-shaped liners operated by a screw and bevel-gears; the studs vary from 0.2–2 in. in diameter; test-pieces may be 6.8 in. long and 2.2 in. wide. The test-pieces may be flattened down by placing them sidewise under the plunger.

608. Fig. 14 shows a bending-machine for flat-bars without bending-stud. The firm describes this machine, which is unknown to me, as follows:

"The characteristic idea of this machine is the adjustability of the holders. The test-piece is not bent about a stud, but bent unsupported, and in such manner that the bending-moment is uniform in every section of the unsupported part. A homogeneous bar will therefore bend to a circular arc. Hence the curve assumed by the bar is a measure of homo-

geneity* of the material and of the position of the neutral axis. The bar is bent by means of a worm-wheel; the bending-moment is measured by a mercury-gauge, and the amount of distortion by a graduated circle. The free length of test-piece may be varied between 0.8 in. to 4.8 in. (2–12 cm). This machine may also be arranged for reverse bending-tests."

609. The Amsler-Laffon holding-devices are shown in Figs. 425 and 426. Fig. 425 is the arrangement of crushing-test machines for crushing and transverse tests. The girder-beam 2 is provided with a rack and a scale, by means of which the supports 7 may be adjusted. These carry two pairs of bearings, 8 and 12, revolving about axes at right-angles, so that they may fit warped surfaces neatly. Crushing-tests are made between platens 3 and 6. Bolt 10 is a dowel to secure 2 in proper position. This dowel may be removed for crushing-tests, thus leaving 2 free to revolve and permit ready access to the test-piece.

In tension-test machines the girder 2 is suspended from the tension-rods 1, Fig. 426. It also answers as the upper tension-holder into which the slide 11, with the bearing-ring 12 or 13, for round or flat bars, is fitted. It is assembled on the floor. The test-piece is then inserted into the slotted slide 22, with which placed on the ribs of the beam 2 in front of the holder it can be gripped after the lower jaws have been raised to the proper height. The holders (Pl. 14, Figs. 15–17), with gripping-wedges for the 100- and 200-ton machines, are copied from the Emery type, having wedges placed in cylindrical guides 4, Pl. 14. The shell 2 is carried on a spherical bearing on piston 1, and surrounds the bushing 3 which carries the wedge-guides 4 and the bottom-plate 8; the latter carries the springs 9 which tend to close the wedges. The two wedge-holders may be moved simultaneously by the

* It must be remembered that this can only be true to a limited extent, for a bar which is equally porous throughout its length, as is easily possible in a rolled bar, may nevertheless bend in a circular curve,

pinion 7, thus causing the wedges to grip or release the test-piece 6. The sliding cylinders contain hardened cylindrical bushings (wedges) 5, having gripping surfaces. To interchange the latter, cylinders 4 are drawn back into the bushing 3 by lever and pinion 7, thus spreading the jaws, and then bushing-wedges 5, which lie loosely in 4, can be readily withdrawn one after the other, and others inserted in their place. The holding-bushings lie loosely in 4, and hence can adjust themselves to the test-piece. Other details are shown by the illustration.

8. French Machines.

(Pl. 15.)

610. In General. Unfortunately I am not able to give more information about French machines than the incomplete sketches taken from publications, which moreover are in part old [compare (*445*) and explanations of Pl. 15]. I have to thank Prof. Paul Debray of Paris alone for some information relating to French machines, for, with this exception, letters addressed to the various manufacturers remain unanswered, not having been returned although being superscribed with my full address. For these reasons I must content myself with the descriptions in Pl. 15 and those previously given. Details of the following machines were described in the sections affixed: Chauvin and Marin Darbel (*558*), loads indicated by diaphragm-gauge; H. Thomasset (*555*), loads indicated as before; Maillard (*445*, *556*, *557*), do.; Curioni-Desgoffes-Ollivier (*455*), band pump; Petit (*510*), loads indicated by float. Descriptions of the machines will be found in the references (*L 102*, *113*, *183*, *236*), some of which also refer to earlier publications.

9. English Machines.

(Pl. 16 and 17.) *L 49*, 1884, p. 180; *55*, 1886, II, p. 27; *48*, 1886, II, p. 176; 243.)

J. Buckton & Co., Lim., Leeds.

611. In General. This firm constructs mainly machines of all sizes designed by its chief engineer, J. H. Wicksteed (*L 48*, 1891, II, pp. 144, 412). The Wicksteed machines have already been discussed in (*485*) and (*519*). It has been introduced extensively and is highly praised. I saw one in the United States, but had neither time to work with it nor opportunity to examine it; I have already expressed my opinion (*485*) about its external appearance, and my objections due to the effect of the inert mass.

Different types of this machine are shown on Pl. 16 and Figs. 7, 8, 9, Pl. 17. They are mostly vertical, but some horizontal, the mighty lever resting on top of the column; it is provided with a very large poise-weight (*519*) which is operated in various ways by mechanical means. These weights are 1 and 1½ tons for the larger machines. The poise in its extreme position on the end of the short arm balances the weight of the long arm (twice as great) and travels across the main fulcrum to the long arm. This reduces the mass to a minimum. The pressure on the main knife-edge is said not to exceed 11,280 lbs. per. in. (2000 kg/cm).

612. The 100-ton machine at Bradford College stands in a pit, and passes through the floor. It is arranged for tension, crushing, thrust, bending and torsional tests. When large pieces are to be tested the floor is removed. The general arrangement is shown by Figs. 11 and 12, Pl. 16, and hardly needs any explanations additional to those in (*519*).

613. Tension-test. In tension-tests loads are applied as shown in Fig. 421 (*599*); the upper cross-head 8 can be adjusted to length of test-piece by the gearing 9 and screws 7, Figs. 1 and 2, Pl. 16. The holders are shown in Fig. 10, as

well as the connecting clamps 36 for string 38 between test-piece and the autographic recorder 36. The string 38 is detachably connected to the lower clamp, passes over a roller on the upper, and a guide-link 37 to the drum 36, which it revolves, while the pencil moves proportionately to the motion of poise 14.*

614. Crushing- and thrust-test. Loads in crushing-test are applied as shown in Fig. 412 (*568*). Figs. 1 and 2 show the machine arranged for a thrust-test of a cast-iron column; the pressure-platens are approached toward each other for a crushing-test.

615. Transverse Test. The principle of device for bending-test is shown by Fig. 427. Power and load-indicator are in indirect action as shown by Figs. 9 and 12, Pl. 16. The construction of the points of application of power is peculiar: two free half-cylinders are fitted in slots in platen 28, from which they are suspended; no provision is made for warped surfaces of test-piece. The recorder may also be used for the bending-test.

616. Torsion-test. Arrangements for the torsion-test are shown in Figs. 3 to 5. The test-bar 34 lies high up at the head of the machine, so that its axis coincides with the edge of the fulcrum, and power is applied by the worm 33 and crank 18. Torsion is transmitted to the recording drum by means of the small wheel 35, Figs. 3 and 5, and a string.

617. A horizontal Wicksteed is shown by Fig. 7, Pl. 17, and its scheme by Fig. 428. Power and load-indicator are at the same end of machine. The indicator consists of an angle-lever 5 suspended from the machine-frame, and a tension-rod 6 converts it into a vertical Wicksteed machine to a certain extent. The load is transmitted from the piston 2 to the frame 3 and adjustable cross-head 9 to the test-piece *s*, to the cross-head 8, the rods 4 and finally to lever 5. Short

* See (*534*) relative to guide-rollers, which is not here observed.

pieces *d* are tested under crushing-pressure between 8 and 2; long pieces between 9 and 10; and transverse tests are made between 10 and 11. Torsion-tests are made as described in (*616*) The machine is provided with a Wicksteed autographic recorder (*727*).

618. Two smaller vertical Wicksteed machines are shown in Figs. 8 and 9, Pl. 17. In addition to the vertical machines, the firm also builds others for tension, crushing, bending and torsion, driven by screw or hydraulic power, as well as for testing chain, columns, bridge members, springs, and bending-tests

Fig. 10, Pl. 17, shows a heavy machine for the latter, and built according to principle described in (*375*) and illustrated by Fig. 253.

Greenwood & Batley, Lim., Leeds.

619. In General. This firm built the universally known machine for D. Kirkaldy in London (*L 121*). This machine has a capacity of 450 tons, and is similar to the more recent large machine shown in Fig. 430. The scheme shown in Fig. 429 is also applicable in essential points to the Kirkaldy machine.

620. The horizontal Greenwood & Batley machines are driven by hydraulic power, the piston 2 acting on the cross-head secured to four screws 3, passing through the adjustable cross-head 4, then through *z* for tension and through *b* for transverse test. The load-indicator usually consists of an angle-lever 7, acting on a poise-beam (Figs. 1 and 2, Pl. 17); in the smallest machines, Fig. 6, the angle-lever carries the poise. In the Kirkaldy machine the scale is arranged to one side and parallel with it, the angle-lever and weighing-beam being connected by a beam swinging horizontally; otherwise the construction of machine and scale is the same as in the smaller machines.

621. The arrangement for tension and transverse

tests will be understood from Fig. 429 and Pl. 17, Figs. 1 and 2. The arrangement for torsion-test is according to scheme shown by Fig. 431. The detail and bearings can be identified in Figs. 1 and 2, Pl. 17. The lever 2, attached at centre of test-piece 3, transmits the force as in 1. Power is applied by means of chains 5 and chain wheels 4 attached to either end of test-piece. These bear on the frame and are braced by rollers 6.

622. Machines for testing wire, textile fabrics, leather, etc., are built vertically as in Fig. 6. A portable horizontal chain-tester is shown in Fig. 4; power is measured by means of a spring-gauge on the hydraulic cylinder.

10. American Machines.

Wm. Sellers & Co., Philadelphia, Pa.

(Pl. 18.) (*L 211, 219, 242.*)

623. In General. While referring to descriptions in (*483, 485, 501* and *559*) I here reproduce my report published by the Zeitschrift des Vereins deutscher Ingenieure, 1895, p. 421. The Emery machines, built by the above firm, show very singular arrangement and detail of the highest interest.

The machines are horizontal. They are operated by a hydraulic press, connected to the load-indicator by two heavy spindles, on which its position on the latter can be adjusted by dowel-pins (45-ton machine, Fig. 344) or by screw-thread. Press and pressure-abutment are secured to the frames or supports (45-t. machine, Fig. 344) by friction. The actual connection between these and the foundation are two spring-buffers, which receive the ends of spindles. The loads are measured on the Emery system, by converting them into liquid pressure (*559*), which is then transferred to an Emery scale (*502*) and there weighed. The movable parts and those which are to move in parallel directions are mainly guided and

supported by Emery's plate-fulcra, which also replace knife-edges in the scale (*501*, *504*).

The 45-ton machine, Fig. 344, can test pieces 39 in. long under crushing-loads and $18\frac{3}{4}$ in. long in tension; the largest pump drives the piston at a rate of 15 in. per min., and the piston travels 24 in. In the 90-ton machine, Fig. 356, the maximum length of pieces for crushing-test is 92 in., and for tension 68 in.; piston-travel = 43 in., and speed $4\frac{3}{4}$ in. per min. In the 135-ton machine these values are 214 in., 153 in., 43 in. and $4\frac{3}{4}$ in.

624. The load-indicator scale is similar in all machines, and is generally based on the following plan:

The block *a*, Fig. 432, receiving the force from the test-piece, is carried by the diaphragms *h*. On it two star-shaped bodies, *b* and *c*, are mounted. During tension-stress the teeth of body *c* bear on the Emery hydraulic support *e*, which transmits the hydraulic pressure produced in it to the scale, while the bearing-pressure (resistance) is transmitted by the intermediate ring *d* to the teeth of the bearing *f*, and by it to the two main spindles, Fig. 344, and finally by them to the press which is fixed thereon, thus maintaining equilibrium in this circuit. To insure firm bearing between *c* and *e*, and *d* and f_1, and also to take up the excess of weight of scale, the spring-cushion (straining-device) *l* to *n* is stressed in direction *l*. At the same time the ring *d*, by a slight revolution of the ring *g* having inclined faces, is caused to bear firmly against bearing *f*, thus preventing shock on the hydraulic support at instant of rupture. To set the device for crushing-test the ring *g* is liberated, and the straining-device *l* to *n* is loaded in direction *m*; this will produce bearing of *b*, *d*, *e* and *f* in the direction of crushing-stress. The equilibrium of forces will be established in the same manner as before. The supporting frame therefore serves but one purpose—to absorb and transmit the excessive inertia of the mass of the machine. Bearings *d* and *e* are also maintained in their positions by diaphragms *i* and *k*,

although in a manner different from that shown in the illustration.

625. In Figs. 1–13, Pl. 18, I reproduce working drawings of the 135-ton machine built by Wm. Sellers & Co. for the Applied Mechanics Laboratory of the Mass. Inst. of Technology, kindly sent me by Prof. Gaetano Lanza; it is one of the earliest Emery machines built by that firm. Figs. 1 to 11 show the details of the load-indicator; the general arrangement in Figs. 1–6, and the special arrangement of hydraulic chambers in Figs. 7–11. [The principles of the construction of hydraulic chambers have been discussed in (*554–563.*)]

The straining-beams 1 and 2 in Fig. 3 are supported on and clamped to the main girders 3. These two beams are connected to each other by the main spindles 4 by means of nuts 5 and 6, and enclose the pressure-chamber or support, Fig. 8. The nuts 6 carry the buffers 7 bolted to girders 3. Beams 1 and 2 support by diaphragms 8 the column 9, to one end of which the holders are attached at 10. This column is star-shaped (see Fig. 432) at its head and carries the second star-shaped casting 11; its end is connected to the straining-device 31–39.

The ring 5, Figs. 3 and 7, is shouldered and fits into recesses in 1 and 2. This ring 5 supports the pressure-chambers by means of a flexible ring diaphragm 12, 13 attached to ring 14, which latter may bear against the ribs of 9 or beam 2 according to the adjustment of the straining-device. Ring 14 supports the flexible rings 15 by means of a clamping-ring, while 16 carries the cover 17 of the annular chamber. This chamber consists of two thin corrugated brass disks soldered at their edges, and containing liquid between them, the pressure of which is transmitted to a smaller chamber in the scale (*559*). The edges of the chamber are turned over and fit in a groove in 18, Fig. 9, being secured by soft solder calked and jammed into place by the rings 19 and 20. These rings at the same time limit

the play of 17 and serve as abutments for the flexible rings 15 and 16. The connection of the tube 21 and the chamber is the plug 23, soldered to chamber 22, fitting in a recess in 18, and the screw-plug 21. The ring 18, like 14, has a bearing surface on its back which bears against the star-shaped body 4 under tension-loads, but against 1 under crushing-loads. The ring 24, in the machine described, consists of two parts having inclined surfaces, which when turned by the double spindles 25 (having right and left threads) will force ring 14 against 1 and 2, and thus fix it. Screw 26 is a limiting stop.

The complete chamber fitted in the ring 24, called the hydraulic support, can be completed in the shop, and shipped as a whole if, by use of bolts and tapped holes 28 and 29 and separating-plugs, the separate rings are rigidly clamped and braced. Hence the complete system of chambers may be independently calibrated on a separate machine.

626. The straining-device (Figs. 1 and 2) is enclosed in a case 30 bolted to the beam 1. Springs 31 and 32 lie between 33 and 34, bolted to 3 by 35. The load in one or other direction is applied by the spindles 36 and a train of gears. For tension-test the frame 33 is moved toward 34; for crushing-test 34 is moved against 33. The motion of the hand-wheel necessary to produce the desired effect is limited by the stops 37, Fig. 2. The application of this device is exceedingly simple. Plate-fulcra are also used to support this straining-device.

627. The tube 21 conveys the liquid pressure produced in the annular chamber to two smaller chambers similarly constructed which are fitted to a steel block 40, Figs. 12 and 13, and bolted thereto by the plug 41. The chambers are formed by the recessed plate 40 and thin steel diaphragms 43 packed on a lead ring and secured by ring 44 and bolts passing through 40 from below. These rings also serve to attach the outer edges of flexible rings 45, the inner edges of which are attached to the movable cover 46, thus maintaining it in a concentric position. The blocks or columns 47 then transmit the

pressure to a beam which bears against the main lever of the scale. The block 40 is placed in the lower right-hand corner of the scale-frame (Fig. 356).

I shall not give a detailed description of the scale as modified by Sellers, because I do not consider it practical any more than the original Emery type, at least not in connection with testing-machines. The old form of Emery scale became well known in Germany years ago through Prof. Reuleaux's reports; I could not obtain drawings of the Sellers type of scale.*

I shall here only indicate briefly that the pressure from the two chambers 43 is transmitted by a block to the lever system connected throughout by plate-fulcra. The scale is composed of several levers and a very light indicator-lever, which makes the motion of levers visible on a largely multiplied scale. All knife-edges are avoided, plate-fulcra (*498*) being substituted therefor. The series of weights are arranged in parallel rows; each series being composed of equal weights one above the other, which are successively deposited by hand-levers, the position of levers indicating the total loads applied.

628. The essential feature of Emery's system of measuring force is, as previously explained (*559* and *L 162*, p. 1027), that the mobility of the chamber-covers is called into play to an exceedingly small amount, thus reducing to a minimum the quantity of liquid in motion during adjustment of scale. Therefore a scale of very large lever-ratios becomes necessary if great accuracy is desired,† and, moreover, the total quantity of liquid in chambers and tubing must be very small, in order

* Unfortunately my efforts to obtain drawings from the firm of Wm. Sellers & Co. failed, and I was thus compelled to limit myself to the information given to me by Prof. Lanza. For this reason I have not described and illustrated the vertical type of Emery machine; it will be found in (*L 219*).

† It is self-evident that otherwise any scale might be used. This condition might also be fulfilled by a Bourdon spring by limiting the play of scale-beams, etc., etc.

that effect of temperature due to changes of thermic conditions of the masses does not become too great. If the scale were simplified and conditions previously stated were met, I believe that the Emery-Sellers machine might be very essentially improved with great success, because it possesses a very important advantage, that of being able to place the load-indicator in any convenient position (*551*, *559* a).

629. The hydraulic press, Figs. 14 to 18, as well as the "support," is also held on the girders 3, but by clamps 48. The press 14 contains a packed piston 58, and works under maximum pressures of 1560 lbs. (110 at.). Suitable mechanism is attached to the cylinder 49 and the cylinder-head, by which the position on the straining-screws may be varied at will. Without going into details it may be stated that this is done by hand-wheel 50 or by belt on 51. The motion is transmitted by the gear 52 to the planet-wheels 53, thence to two pairs of bevel-gears by a shaft passing through the other shaft to the gears 56 and 57. The gears 57 act as bearing-nuts for the press, and revolve on the straining-screws 4. By gearing the planet motion these nuts will be adjusted with equal tightness on both screws. Most of the movable parts are protected by covers. There is about 4 in. play between the nuts 57 and their bearing-surfaces on the cylinder 49, which permits it to move a certain distance at the instant of rupture, thus absorbing its recoil by the friction of clamps on girders 3, which can be adjusted by bolts 48. The feed-pipes on the cylinder are jointed, thus following all motions of the cylinder readily.

630. Sellers builds a very good power-pump for operating the press, illustrated in Fig. 335 (*459*), the delivery of which can be regulated at will during motion by raising or lowering a box-link, thus changing the throw of the three plungers from 0 to 5 in. The pump has three-throw cranks at 120°, and a delivery of 4 gals. per min. at 110 revol. (or about

$\frac{3}{8}$ cu. ft.). This pump has a very neat appearance and, according to repeated demonstration, works admirably; it requires little space, and may be particularly recommended when a single machine is to be operated.

631. The Emery holders are shown in Figs. 19–32. The tension holders consist of a steel block 2, containing two cylinders 1 arranged to take the gripping-wedges, and sliding in bored holes the axes of which are inclined to each other. The whole device is attached to the straining-head 3 by a fine thread, or to the end of piston-rod 58, Fig. 17. The grip holders may be moved forward and back by means of the screw 5, the nut 6 of which dovetails into cylinders 1, thus opening or closing the jaws. This motion is produced by spindle 7, which carries a worm-gearing with the worm-wheel 15 enclosed by 10 and 11. This wheel encloses the spindle but partially and runs free for about $\frac{1}{4}$ revolution, then striking a projection on the plate 14 bolted to the spindle. A spiral spring 18 is enclosed between 14 and 15. For the purpose of gripping the test-piece by means of 7, 15 and 14, the screw is set up hard to overcome the resistance of the spiral spring, causing the serrated wedges 16 to press into the test-piece and the smooth liners 17 to fit it snugly [in the United States test-pieces without heads are much more frequently used than in Germany, and hence serrated wedges are more generally used]. When the wedges 1 advance during test the pressure on screw 5 is gradually released and spring 18 comes into play, causing the spindle 5 to follow the wedges 1; this necessitates the $\frac{1}{4}$ revolution of free motion. The screw 5 has a double thread of $1\frac{1}{4}$ in. rise. Pieces 1, 17 and 19 are made of tool-steel. 19 to 21 serve to secure liners for material of different thickness; liners for rounds and flats are provided. Special liners are used for shouldered test-pieces. The holder carried by the piston-rod must be supported when the latter protrudes considerably from the cylinder; the beam 22 shown in Figs. 34 and 35 serves this purpose.

632. Holders when fitted with sliding gripping-wedges, even when as well designed and built as the Sellers-Emery, are not suitable for use of instruments of precision (mirror apparatus), which, as well as nearly all really reliable apparatus, are sensitive to shock, and whose construction demands approximate fixedness in space (as of mirrors). Even with this device it is not possible to grip the test-piece so rigidly initially that the wedges will not slip later on. In fact it may be said that the application of sufficient force to avoid this is contrary to Emery's principle of construction; for he screws his holders firmly to the machine detail, and permits the motion necessary to cause the wedges to grip the test-piece by overcoming the piston-friction. I have frequently noticed that particular attention was paid during test to see that the wedges held the test-piece firmly, a proof that this is not always the case; in fact I observed personally that the wedges slipped considerably in the jaws.

I have become convinced in general, from many experiences with other simpler although less perfect gripping-devices, that it is better, when using gripping-wedges, to design them in such manner that the necessary pressure to firmly hold test-pieces may be applied initially, and to entirely avoid automatic wedging.*

633. The holders or platens for crushing-tests are shown in Figs. 31 and 32. They are screwed on to the machine like the tension holders, and the platen 23 may be adjusted on a spherical bearing by the studs 24.

When comparing this design with many used in Germany, I consider this one imperfect. Our devices generally use the concave spherical bearing, with the centre above instead of below the platen, or toward the test-piece, while it is the reverse in the Emery-Sellers holders. Our holders have

* Emery applied this principle in his 150-ton machines which were built for the Cambria Iron Co. and the Bethlehem Iron Co., but not in smaller machines.—G. C. Hg.

the advantage that the platen may be left free during thrust-test, and permit tests with movable bearings to at least a certain degree. If the centre of sphere be laid within the abutment taking the pressure of the test-piece, this point will not shift even if the device be adjusted obliquely; it is also certain that the concentric rings on the platen always indicate the axis of pressure of the machine, if it had been set correctly originally, for which means may be readily supplied. In the Emery device the centring lines are shifted with each adjustment, and only when the ends are parallel, which is of course their usual condition, will they be in correct position. Our construction generally causes more loss of free space between platens in crushing-test.

634. Figs. 433 show the later, somewhat modified form of the Sellers design of pressure-support, as embodied in the machine exhibited at the World's Fair in Chicago in 1893. The weighing-head (Fig. 433*a*) consists of two circular or annular beams, 65 and 69, firmly secured together by bolts placed around their periphery and by the straining-screws which pass through both beams and clamp them by a shoulder and nut. This head and the straining-head fit easily upon the bed which maintains the axes of the two heads in the same straight line. A draw-bar, 70, is secured in the axis of these beams by two thin annular steel plates, 72; these plates hold the draw-bar securely in line with the axis of the machine, while permitting a free motion to a limited extent in the direction of the axis. The projecting end of the draw-bar is provided with a screw-thread by which the compression platform or the tension holder is secured to it. The draw-bar is enlarged in the middle, and against each of the two shoulders thus formed is secured a thin annular steel plate, 73; these plates are for the purpose of carrying and centring the hydraulic support, which is made annular, instead of circular, as shown in Fig. 400. The hydraulic support is maintained in fixed relation with the draw-bar laterally, while it is left free to

move relatively to it in the direction of its axis through the small distance required. On each side of the hydraulic support steel collars, 71, are screwed and secured to the draw-bar; these collars are provided on the periphery with a series of ribs (Fig. 433*c*) parallel with the axis of the draw-bar, and which lie between, without touching, similar ribs projecting from the interior surface of the annular beams. The ends of all these ribs on the two beams and the collars are accurately faced to true planes at right angles to the axis of the draw-bar, and the distance between the two extreme faces of the hydraulic support is made slightly less than the distance between those two planes. Movement of the draw-bar in either direction carries the hydraulic support against the ends of the ribs in one annular beam, brings the ends of the ribs on one of the collars on the bar against the opposite side of the hydraulic support, and produces pressure on the contained liquid which is transmitted through the pipe 63 to the small hydraulic chamber in the scale.

In order to prevent the shock of recoil, resulting from the rupture of a large specimen of high steel, from doing injury to the thin brass plates in the hydraulic support, the abutting piece 64 of the support which rests against the ribs in the annular beam 65 when strains of tension are applied is made larger in diameter than the hydraulic support proper, and is provided with a spiral or screw face, 66, which engages with a corresponding screw-face formed on a rotatable ring, 67, fitting in the other annular beam, 69. After the initial load has been applied, this ring is rotated by the pinion-shaft 68 to bring the screw-faces in contact, see Fig. 433*b*, and the abutting piece 64 is thus clamped firmly to the annular beam against which it rests. When the specimen breaks, its first blow is delivered through the draw-bar and ribbed collar to this abutting piece 64 which transmits it through the ring 67 to the rear annular beam 69 and as these beams, 65 and 69, are rigidly united, the blow is absorbed by the total mass of these two beams.

The hydraulic support is thus thoroughly protected, and these machines can be used regularly for breaking high-steel specimens up to the full capacity of the machine without any risk of injury.

The weighing-head is returned to its place on the bed after movement due to recoil by a set of spiral springs locked up in boxes secured to the bed; these springs are strong enough to move the head, and their resistance diminishes greatly the movement due to recoil, while the friction of the head upon the bed rapidly wipes out the oscillations. The annular beams bolted together, as described, constitute one built-up beam to rest the bending due to the pressure on the draw-bar midway between the straining-screws. The hydraulic support is thus enclosed in a rigid mass of cast-iron and effectually protected against injury from violence or from being gummed up by oil from the straining-cylinder, as has occurred with the upright machines, and the frictionless movement of this support under all conditions of service is thus insured.

635. The constructions described in (*625–634*) are admittedly masterpieces of engineering; they have found their champions in Germany, as also in other countries; but it is possible that the unbounded praise was one-sided, and therefore I consider it my duty not to be satisfied with a mere description, but to express my doubts about and objections to the Emery machine, because experience has taught that there is nothing entirely perfect, and a recognition of defects will most surely lead to improvement.

Riehlé Bros. Testing Machine Co., Philadelphia, Pa.

(Pl. 19.) *L 51*, 1881, p. 147.)

636. In General. This firm constructs an unusual variety of testing-machines of all sizes and for the most varied purposes. Their machines are largely distributed throughout the United States, and beyond their boundaries. A detailed description of the many types cannot be here given, because the

essentials have been presented in previous paragraphs, and because I shall later on again refer to specialties relating to devices for measuring deformation. I shall therefore take up only special points to complete previous descriptions.

637. The machines illustrated on Plate 19, Figs. 1–5, are as a whole based on the scheme shown in Fig. 366 and described in (*526–528*). A study of these illustrations and of the operation of the machines themselves cannot remove the impression of fundamentally unnecessarily complicated construction. It is not an easy matter, especially in those machines in which the poise is operated automatically by electrical devices, for the observer to become familiar with all the necessary manipulations and matters requiring constant attention. What is here stated applies equally to the similarly constructed machine of Olsen, Pl. 20, and to all equally complicated structures; I emphasize this subject at this time only to encourage, to the best of my ability, simplification in construction and operation of testing-machines.

638. The large Riehlé machines have special devices for making tests of all kinds, such as tension, crushing, thrust, transverse, shearing, punching tests, etc. Fig. 6 illustrates a torsion-test-machine, and explains itself; the numerous small machines hardly need further explanation than given by Pl. 19.

639. I wish to mention that the firm states that two of its machines were tested by direct loads of 50,000 and 100,000 lbs. at Sibley College, Cornell University, and errors of but $\frac{1}{10}\%$, and practically constant, were found.

Tinius Olsen & Co., Philadelphia, Pa.

(Pl. 20.) (*L 102; 113, 51*, 1879, p. 36, and 1883, p. 39. *42*, 1896, p. 91.)

640. In General. Olsen & Co., the same as Riehlé Bros., also build a respectable number of machines for all kinds of tests. In arrangement and external appearance the

machines of both firms are generally very similar; in details they differ somewhat. Olsen's machines are also distributed far beyond the boundaries of the United States; they, with the Riehlé machines, are the really commercial machines in the United States; I found machines of both firms in nearly all works and shops which I visited. I shall not describe these machines in detail here, because the scheme of the separate arrangements is given in Fig. 365, and other details have been discussed in (*525*); the recording-devices will be discussed later on.

These machines are also provided with means for making tension, crushing, thrust, transverse, punching and shearing tests. Machines for making torsion-tests are shown in Figs. 31 and 32. The device Fig. 32 is used in machine shown by Fig. 16. In it the torsional moment is generated by a worm *H* and measured by the scale by transmission from test-piece and the rod *G*. Fig. 31 illustrates a special machine for torsion-tests for large pieces, in which finished shafts may be tested.

640a. The Thurston Torsion-machine, fully described in Thurston's "Materials of Engineering," Part 2, is a pendulum-scale in which a very short test-piece, 2 in. between shoulders, is placed in the axis of revolution of the pendulum, loads being indicated by the angularity of the pendulum It is applicable for torsion-test alone.—G. C. Hg.

641. Fig. 33 is an impact-machine designed by W. J. Keep, slightly modified by Chas. H. Heisler (*L 42*, 1890, p. 91) for tests of cast iron under impact. The pendulum strikes a pin which acts at the centre of a bar supported at two points of the cast test-piece. The latter is subjected to an impact bending-test.

642. A 50,000-lb. Olsen machine was calibrated by Gus. C. Henning by direct loads up to 21,000 lbs. The degree of sensitiveness was determined at the same time by adding and removing small weights, so that the balanced lever moved up or down $\frac{1}{8}$ in. under this change of load. The re-

sults of this investigation are plotted in Fig. 434. The heavy full line of averages shows that the degree of accuracy diminishes with increasing loads, for the generally positive error of equilibrium (full line) grows in proportion to the heavy broken line from about 0.1% to 0.4% for 30,000 lbs. load. The degree of sensitiveness ($\frac{1}{8}''$ vibration) is uniformly about $0.0007P$ (load).

643. The data given in (*488*, *506*, *509*, *512*, *529*, *534*, *543*, *546*, *556*, *603*, *639* and *642*), relating to calibration-machines, show that testing-machines used in routine work **may possess an accuracy of 1%, which has been considered sufficient, but that requirements should not be made much higher than this.**

V. Measuring-Apparatus.

Introduction.

644. Measurements made in testing materials usually consist in determination of original shape, of deformations occurring during test, and of final shape after test. Measuring-apparatus employed for determining original and final shape of test-pieces do not as a rule differ from those ordinarily used in machine construction or for other purposes. I shall therefore merely enumerate them. The apparatus necessary for measurements of deformation during test require, however, close study, in so far as the underlying principles and the theory of the instruments have not been discussed in previous paragraphs.

A. Measuring and Measuring-Apparatus.

a. Measuring.

645. Measuring consists in comparing the unknown with the known; in measuring lengths the unknown lengths are to be compared with known lengths, scales, either directly or indirectly. Direct comparison is generally made by placing a scale directly on the body to be compared. Indirect comparisons are made by use of auxiliary apparatus, to which the length to be measured is first communicated, and then determined on the scale. Measuring is an art which

must be acquired, and which requires very strict attention, as well as reliability of observer and of instruments, if perfect results are demanded.

646. No measurement can be made with absolute accuracy; every measurement contains errors, the source (cause) of which may lie in the observer, as well as in the apparatus used, and in the method of using the latter, and finally in external circumstances, under which it must be used at different times. Certain classes of sources of errors, depending upon methods employed, are distinguished:

a. Errors of observer, personal equation; experience, skill, sight, touch, temperament, etc., play a part.

b. Errors of instrument; inaccuracy of scales, inaccuracy of divisions, width of lines, inaccuracy of motions, etc., produce an effect.

c. Error of method; the kind and manner of making a measurement, or how an apparatus is used, the arrangement of the measurement, etc., may lead to errors of varying magnitudes.

d. Errors of external origin; thermal, hygroscopic changes, etc., may change the scale or the body to be measured: the kind of illumination, convenient or inconvenient position of scale, etc., may be causes of errors.

Sources of errors of the above classes are generally coincident.

647. Sources of errors are furthermore divided especially into those which regularly produce an effect of a certain kind on results of measurements, hence shift the result of measurement either positively or negatively from the true value of the length measured; errors of this kind are called comprehensively methodic errors, to distinguish them from those which are principally due to unknown causes, to accident, and affect the result uniformly in a positive and negative manner. These errors are collectively designated as accidental errors.

The problem and art of the observer consist in making the errors as nearly harmless as possible, and the result as nearly free from methodic errors, and reducing accidental errors to a minimum, or determining their values.

The first rule of the art of measuring is to avoid methodic errors, or to determine them mathematically and to correct them. The observer must know the sources of errors and the laws governing them, or determine them experimentally. The use of different methods for determining equal dimensions or the change in arrangement of measurements may eliminate methodic errors.

Accidental errors of a series of measurements are as a whole subject to definite mathematical laws, which have been very fully developed in numerous works on "averages," on "theory of probabilities," and in handbooks on physics (*L 103, 104*).

As mostly simple repeated observations of the same values (measurements and weighings) are made in tests of materials, I shall briefly enumerate the simple conceptions, but refer to special literature for the remainder.

648. Accidental errors are such which individually show no underlying principle, but which are produced solely by accident. Among a great number of observations of the same magnitude there will be as many positive as negative errors of equal value, and the smaller errors will be more numerous than the larger.

If the same dimension has been observed by oft-repeated measurements, the mean of all values will approximate the true value most closely; the mean of all observations is in this case the most probable value of the dimension measured. The small errors will balance each other; the coarse errors occur isolated, and, as far as they do not counterbalance, their effect is diminished by finding an average. The difference between the value found and the mean is determined for each observation, and this is called the

error of individual readings. If these errors depend solely upon accident, they must evidently be large and small, positive and negative, and without regular sequence. Hence the irregular appearance of opposite signs, and lack of grouping or regular arrangement of errors, is an indication of reliability of observation. Furthermore errors of equal value (especially the small ones) should be as frequently negative as positive. The assumed method of determination of error presupposes that the sum of positive and negative values be equal to 0. If the number of individual readings, i.e. of errors, be great, the frequency of positive and negative values must show a definite law. If the errors of an extended series be arranged according to equal values and same sign, a correct series must give the diagram shown in Fig. 435. The curve has a maximum for small errors, and is symmetrical toward both ends. The hatched surface shows the sum of all negative errors of an extended series of observations. That ordinate which bisects the diagram cuts off the error $-r$; the same is true of the positive end of the diagram. The probability of an error being smaller than $\pm r$ is just as great as that of its being greater than $\pm r$. The value $\pm r$ is a characteristic standard of quality of measurements; it is called the probable error of observation.

If m be the (great) number of observations (errors), then the number of errors less than $\pm r$, according to the foregoing, will be $m \times 0.500$, and, according to a well-known law applying to frequency of accidental errors, the number of errors of a certain value is:

$$\pm (0 \text{ to } 1r) = m \times 0.520$$
$$\pm (0 \text{ to } 2r) = m \times 0.823$$
$$\pm (0 \text{ to } 3r) = m \times 0.957$$
$$\pm (0 \text{ to } 4r) = m \times 0.993$$
$$\pm (0 \text{ to } 5r) = m \times 0.999$$

Hence it is to be expected that an error greater than $5r$ will occur but once in 1000 errors. I have inserted the previous values in one half of the diagram, Fig. 435. The foregoing will readily show the importance of the probable error for judging the accuracy of observations.

649. Without entering upon the subject at greater length, I wish briefly to explain that the *probable error of an observation*, as well as the *probable error of the average value* of series of observations, is determined from the series of differences of m observations A, A', A'', etc., by the ratio $\frac{\Sigma A}{m}$, by obtaining the differences $\Delta = A - m$, $\Delta' = A' - m$, $\Delta'' = A'' - m, \ldots$, etc., and adding the squares. From $\Sigma\Delta^2$ the *probable error of a single observation* is then obtained from:

$$r = \pm\, 0.67449 \sqrt{\frac{\Delta^2}{m - 1}}$$

[for calculation : log 0.67449 = 0.8289755 − 1];

and *the probable error of the average of the series of readings*:

$$r_m = \pm\, 0.67449 \sqrt{\frac{\Delta^2}{m\,(m - 1)}}.$$

It will be seen that it is possible to reduce the absolute magnitude of values r and r_m by increasing the number of readings of equal accuracy, but it is to be preferred, and generally is more economical, to make the value Δ^2 as small as possible by the application of greatest possible care.

The further use of the theory of averages and of probability of errors is explained in the works quoted (*L 103, 104, 252*).

b. Scales.

650. The scales used for measuring length are either r u l e d or e n d s c a l e s (gauges). Ruled scales are marked on their surfaces by dividing lines, and subdivisions of the unit of measurement permit direct reading of lengths. End scales, gauges, always represent but one definite length, given by the distance between the terminal surfaces. The method of measurement varies according to the type of scale used, and we may distinguish between l i n e m e a s u r e m e n t s and e n d m e a s u r e m e n t s. L i n e m e a s u r e m e n t s may be made by direct adjustment of the scale to the piece to be measured. Scales intended for this method are called r u l e s.

Very frequently it is, however, impossible to adjust the scale properly, and then auxiliary apparatus is used to compare the length to be measured with the scale, as the dividers, gauges, verniers, microscopes, telescopes, etc., which are shifted on scales until coincidence of lines is reached. In end measurements it is almost always necessary to use such auxiliaries and then transfer them to line measurements if it is desired to determine the difference between such length and the end gauge. As a rule, however, e n d s c a l e s are used for production of like bodies; e n d m e a s u r e m e n t s are, however, very frequently made by use of tram-gauges, contact-levers, sliding-gauges, micrometers and other devices.

I cannot present a complete exposition of methods of measurements, but must limit myself to those points which I consider important in testing materials, and wish to present certain points of view for practical measurements, without adhering to a definite order.

651. The a c c u r a c y o f m e a s u r e m e n t s m a d e w i t h a r u l e d s c a l e, or of divisions in general, depends upon the accuracy of the scale and its divisions (its external and internal errors), and also upon the m a g n i t u d e o f t h e d i v i s i o n s. Tenths of division are estimated most

correctly, according to experience, when the divisions are from 0.03 to 0.05 in. (0.8 to 1.3 mm) in width; finer and coarser divisions produce greater errors of estimation. The thickness of lines, their sharpness, the condition and color of surface divided, and the color of the lines, affect the error of estimation. The thickness of line should be properly proportioned to the width of space, to avoid involuntary differences in the estimated tenths near the lines and at the centre of spaces. The edges must be sharp and smooth, especially on scales which are to be read by microscopes.

In case of a rule the character of its body is of importance. A scale having a sharp bevelled edge, like a paper-cutter, admits much better adjustment to surfaces which carry the limiting marks of the length to be measured than a scale of rectangular section and thick edge. In most cases where a scale is used the divisions cannot be made to touch the limiting line directly, but the coincidence must almost invariably be adjusted by eyesight. The line of sight passing through gauge-mark on test-piece and division of scale must always be normal to the latter; if this is not the case, the error of parallax will exist. When points do not lie in a plane, there will be apparent shifting (parallax) if the eye move with relation to their connecting line; the readings will differ when the line of sight is along ab and a_1b (Fig. 436); the error of parallax depends upon the angle betwen line of sight and axis of scale, and upon the distance b from the marks on the scale.*

If it is desirable to measure accurately, another methodic error must be minimized, which occurs particularly with the

* My method of using a scale, which should be of polished steel or other metal, is to place the scale parallel to the axis of the test-piece and at any convenient distance, and in such manner that the image of the gauge-marks can be plainly seen in the scale. By matching the reflected gauge-marks with the scale divisions very accurate readings can be easily made.—G. C. Hg.

use of finely divided scales, that of adjusting the end line of the scale to an end mark on the object. The eye judges differently of the coincidence of end mark and that of any intermediate dividing line. The measurement is already affected by attempting to produce coincidence of a given scale division with one gauge-mark and reading the position of the other on the scale; it is much more correct to place the scale arbitrarily on the object and then to read off each mark independently wherever it falls on the scale and then find the actual length by difference between the two readings.

The perfection of illumination, convenience of position of object and of scale with respect to the position of the observer, the circumstance whether the latter can take readings leisurely, sitting or standing, have a far greater effect than is generally assumed. All of these matters can easily be corroborated by the ordinary methods and use of scales commonly applied in machine construction. In order to accustom students to reliable work, and to impress them with the above sources of errors, they are drilled in measuring the distance between lines on metal plates, each group working under different conditions, using different scales. Each of a group of 10 observers makes 10 measurements, the averages are found, and their probable errors determined to eliminate personal equation and to make the awkwardness of individual observers harmless. Such a group of measurements is given in Table 44.

652. Tools for end measurements are largely used in construction in the shape of c a l i p e r s; they are scarcely ever used in testing materials at present. The use of s l i d i n g and s c r e w - c a l i p e r s in construction is a transition to line measurements; both are largely used in testing materials. Sliding calipers usually permit readings as fine as 0.001 in. by means of a vernier (or 0.1 mm), and estimations to 0.0005 in. (or 0.05 mm by metric gauges). But ordinary trade instruments are rarely sufficiently accurate to insure reliability of readings. H e w h o w i s h e s t o u s e s u c h i n s t r u -

ments for accurate measurements will do well to obtain them from reputable manufacturers, and then to calibrate them, or to have them calibrated by proper authorities (scientific institutions, or governmental offices charged with calibration of weights and measures), and certified.

Table 44. **Probable Error of Measurements of Length between Lines by Scales of Different Divisions.**

All values refer to 30 readings.

Value of divisions in mm.	Probable Error				Kind of Scale.
	of Observation		of Average Value		
	in Spaces.	in mm.	in Divisions	in mm.	
3	0.0038	0.0114	0.0007	0.0021	Bevelled edge, brass.
3	0.0080	0.0240	0.0015	0.0045	do. do.
1	0.0199	0.0199	0.0036	0.0036	Ordinary mm scale, 15 mm thick.
1	0.0038	0.0038	0.0007	0.0007	Bevelled edge, wood scale.
1	0.0057	0.0057	0.0010	0.0010	do. do.
0.5	0.0230	0.0115	0.0048	0.0096	do. ivory scale.
0.5	0.0144	0.0072	0.0026	0.0013	do. do.

The various forms of calipers, verniers and screw-gauges may be assumed to be well known, and require no description if it is added that the remarks in previous paragraphs apply to them, and that micrometers are specially discussed in (*653–659*). In reference to verniers it may be remarked that it is desirable to provide them with divisions additional to the necessary 9 of the scale. This permits ready examination of the accuracy of the divisions of the scale, by taking repeated series of readings of all scale-divisions by the vernier and then finding the probable errors.

C. Micrometer-Screws.

653. In addition to screw-gauges, micrometer-screws are largely used in testing materials for all kinds of precise measurements. The following descriptions of instruments used for measuring deformations during test will show how the preference for micrometer-screws prevails in some countries.* It seems therefore necessary to explain their properties somewhat more in detail, although it is impossible to treat this extensive subject exhaustively.

I have briefly stated the objections to use of micrometers in testing materials in (*80*). A micrometer is an admirable and practical auxiliary if it be used for the determination of very short lengths only (measurements between scale-divisions, shifting of cross-hairs), but it becomes inconvenient and impracticable if great lengths are to be measured which require many revolutions.

654. The errors of micrometers may be classified as follows:

a) Errors of the screw;

b) Errors of motion (error of instrument).

Errors of screw may be again subdivided into:

1). Variation of shape of screw from that of a true cylinder;

2) Progressive errors;

3) Periodic errors.

Inaccuracies of bearings are of a manifold nature; they may even produce periodic errors if the thread itself is quite correct.

655. Screws with notable progressive errors should in no case be used in measuring, because they indicate gross defects in fabrication. A pro-

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*This is mainly due in the United States to the admirable micrometers manufactured by several reputable firms, and their cheapness.—G. C. Hg.

gressive error exists when a micrometer gives different readings of the same object, when readings are taken with different parts of the screw, or when equal revolutions of the micrometer starting from the same division give increasing or decreasing lengths. If a screw-thread be considered as unwound from a cylinder, its development *oa* on a plane will be a right line at an angle α to the horizontal, Fig. 437. The screw having a progressive error will produce a curved line oa' or oa''. A complete revolution of the micrometer, say from $2R$ to $3R$ with a correct screw, will, for every other revolution, advance the screw by a distance $= l$. The screw developing the line oa', having progressive errors, does not advance a distance l for one revolution R_2 to R_3 by l'_3; while for revolution R_3 to R_4 it is $= l'_4$ and for R_4 to $R_5 = l'_5$, in which $l'_3 > l'_4 > l'_5$, etc. If such a defective screw were to be used, a different table of corrective values would be required for each revolution or for each thread of the screw.

656. A screw which advances equally for each complete revolution, always beginning at the same point of the head, may still have noticeable errors. These errors will only be recognized if the same object be repeatedly measured, each observation beginning at a different division of the head, and making a comparison of the results. All measurements made from the same initial reading will be alike, but those beginning with initial readings $0.1R$, $0.2R$, $0.3R$, etc., will vary. Such errors are called periodic errors; their cause may lie in the screw as well as in the apparatus (*654*). A helix with periodic (but free from progressive) errors will not develop as a straight line $\overline{ao}$, Fig. 438, but will be sinuous, about as in oa'.

A micrometer having the periodic errors plotted in line oa' would have different travel for $0.3R$ of l_0, $l_{0.5}$ and $l_{0.9}$ if the rotation of screw had been started at $0.0R$, $0.5R$ and $0.9R$, or at $1.0R$, $1.5R$ and $1.9R$, etc. This screw would require but a single corrective table for one revolution. In determining errors it will of course be necessary to make a greater series of

observations extending over all of the threads which might later on be used for measurements. The average error of observations of the same object, made from the same initial division of the head, is then found and the curve of errors (period) is plotted. Such measurements take time, and should occasionally be repeated because the constants of the apparatus may vary; causes of periodic errors of instruments, particularly, may change (*654*, *657*, *664*); these changes are rarely noticeable superficially. Micrometers should therefore be carefully handled and protected if accurate results are desirable. This is especially true of instruments with threads as fine as presupposed in (*80*).

657. The errors of a screw (of thread) are always produced during manufacture. Their causes are frequently so thoroughly concealed that their determination requires very exhaustive but also very instructive investigation. These cannot be here discussed, but I shall refer my readers to the numerous treatises on the subject contained in the various volumes of the "Zeitschrift fuer Instrumentenkunde" and other works. I desire to use an exaggerated example to illustrate the possibility of existence of periodic errors even if the screw-thread is perfectly accurate. Suppose S in Fig. 439 to be a micrometer-point against which a spring F presses the surface K; this surface being imperfectly finished stands obliquely to the axis of the screw. This error is of no importance as long as the point of the screw has no play and the micrometer will work correctly. But should the point be eccentric or play about the axis of the screw, a periodic error will be produced, the value of which can be readily calculated from the angle of surface of contact and the eccentricity of the point; a periodicity of 0.000026 in. (0.001 mm) will be produced by an eccentricity of only 0.0039 in. (0.1 mm) (or $\frac{1}{10000}$ in. for $\frac{1}{100}$ in. eccentricity) when the obliquity of contact-surface is only 17.2 min.

658. The errors enumerated, however, by no means ex-

haust the list of sources of error of a micrometer apparatus. Each guide or slide may introduce errors. Clearances in detail or play between screw and nut should be particularly considered. The neglect of these sources of error may cause very material uncertainty of measurements. The screw must fit the nut perfectly, without being tight, especially as perfect maintenance of surfaces of threads demands lubrication. The mechanic tries to guard against clearance by providing springs, causing the same surfaces to be constantly in contact. In lubricated screws this occurs only conditionally, as Fig. 440 shows. The nut M is steadily pressed in direction M by the springs provided. The screw will tend to move the nut in the direction of arrow S drawn full, when advancing, and in that drawn dotted when receding. When advancing, the screw pushes the nut; the spring is pressed more forcibly; the screw must overcome spring-pressure and friction. When receding, the spring pushes the nut; the pressure of the spring is reduced; it must overcome the frictional resistances. This clearly shows the causes of errors following definite laws, which as a rule are very small, but must be considered in screws used for very accurate measurements. In each reversal of motion the lubricant must flow from one face of the threads to the opposite, because the width of the clearances must change in proportion to the resisting pressure, as indicated by the dotted position of nut in Fig. 440. But, as the resistance varies with the stress of the resisting spring, the thickness of layer of lubricant is different for each position of screw. This produces errors (although very slight) of the progressive kind. Time, however, also plays a part; for as the lubricant between bearing-surfaces must flow in very narrow spaces, and the differences of pressure are usually minimized by the use of opposite springs of nearly equal resistance, a considerable interval of time nevertheless elapses before the oil flows from one face to the other under the varying pressures; this must of course produce

errors, because the slide (carried by the nut) may still move after the screw has come to rest. All of these errors are, however, as a rule, very small; they would, nevertheless, have to be considered if micrometers were to be made of the same efficiency as mirror apparatus.

659. I have carried this discussion rather further than customary when considering measuring-instruments used in common practice. But I had the object of shaking up the customary sublime confidence which engineers sometimes have in palpably questionable micrometer-screws, and at the same time to avoid the necessity later on of referring to all of these points in the discussion of the individual instruments.

d. Microscope and Telescope Micrometers.

660. Micrometers are exceedingly valuable in connection with reading microscopes and telescopes, for the purpose of measuring, by a very few revolutions, the displacement of the cross-hairs in the field of view of the instruments.

The micrometers thus used are placed in special chambers in the tube of the instrument. They contain a slide on which cross or parallel hairs (spiders' lines, quartz threads) are mounted, or fine lines cut on glass plates. These threads are shifted with the slide across fixed lines or marks by means of the micrometer. The fixed and movable marks (threads) of the micrometer should be as nearly in one plane as possible. An eyepiece is focussed on them; then the instrument (microscope or telescope) is focussed on the object in such manner that its image coincides accurately with the plane of the cross-hairs, in order to avoid parallax. The accuracy of coincidence of planes of image and of cross-hairs is determined by moving the eye forward and back across the eyepiece. In this case there should be no apparent shifting between the image and cross-hairs.

661. If such micrometers are to be used for measuring greater differences in the image, hence requiring several revolutions of the screw, devices are generally provided which indicate the number required to shift the cross-hairs from o to coincidence with the object, or, in other words, the length of screw used in the measurements. These devices, in simpler instruments, are so-called serrations, the teeth indicating revolutions, and appear in the field as shown in Fig. 441; every fifth tooth is marked by a hole. The teeth should be considered as numbered (say with 10, 15, 20, as in Fig. 441). The movable double line is (unless the divisions have been previously calibrated by special series of measurements) made to coincide successively with both lines 1 and 2 to be measured. The readings of the serrations and on the micrometer-head may, for example, be:

$$\left.\begin{array}{lll}\text{Line 1, reading} & 8.823R \\ \quad \text{“} \;\; 2, \quad \text{“} & 17.743R\end{array}\right\}\text{Diff.} = 8.924R.$$

Hence if lines 1 and 2 are those of a millimeter-scale,

$$1 \text{ mm} = 8.924R.$$

Hence the centre line of field of view (tooth 15) coincides with reading

$$1 + \frac{15000 - 8.823}{8.924}\text{mm} = 1.692 \text{ mm}.$$

This method of reading by adjustment to both lines eliminates the errors of adjustment of microscope, i.e., its magnification, as well as the knowledge of actual value of one revolution of screw, and each measurement gives a new value for the determination of the values of divisions of the divisions read.

662. More modern micrometers are generally provided with lines ruled on glass. In this case numbered scales are usually placed on the glass plate, thus

reading the motion of movable plate, in complete revolutions, directly on the scale. Counting the serrations is obviated.

663. In order that the zero of the head coincide with the line approximately (more is unnecessary) when adjusting the movable to the fixed line, the head is usually provided with a conical friction-bearing; it may therefore be adjusted to a correct position by revolving it on its axis.

664. The movable line of micrometers is usually a double line *a*, *b*, Fig. 441, so that the mark is made to fall between them, which is much more accurate than in adjusting one dark line to a black mark. It must here be repeated that lost motion should be minimized by adjustment of both lines in the same direction, either from the right or from the left hand. The amount of lost motion may, however, be determined very easily, by first adjusting both lines from the right and again from the left hand; the difference of the readings for the same line is the lost motion.

665. An excellent instrument having the device just described is the "spherometer," model III (for measuring thickness), designed by Abbe, and built by Carl Zeiss, Jena (*L 56*, 1892, p. 307).* The apparatus is constructed in such manner that the readings are taken on a scale which is used as a direct standard of comparison with the length to be measured; this scale is the rectilinear continuation of the piece to be measured. Abbe used these principles of design because it was easy to make accurate divisions of length, and because a scale can be readily calibrated by a comparator by the method described in (*661*). If the length to be measured lies in the same line with the measuring-scale, the errors of the motion

* The firm also builds a smaller one, model II. In this apparatus the support *A* is replaced by a triangular prism, on which the microscope arm and scale slide, so that variations of 2 in. on a length of 8 in. may be measured directly. The slide is set by means of standard end gauges. The scale is 2 in. long.

of the carriage or slide can have but very slight effect on readings.

The comparator used at the Charlottenburg Testing Laboratory permits measurements of 4 in. (100 mm); it will be specially improved for the calibration of the Martens mirror apparatus (*692–699*), for which heretofore the Klebe-Bauschinger apparatus (*669*) was used. An iris shutter is provided for centering balls (bicycle balls) to be measured.

e. Micrometers for End Measurements with Contact Devices.

666. In use of ordinary screw-micrometers, Fig. 443, measurements are made by adjusting the contact as uniformly as possible by the touch of the fingers, by turning the head of screw 3 until the end touches the end of screw 2 or the object. Whole revolutions are read off on the sleeve 4, subsidiary divisions on the sleeve 5. Screw 2 serves for adjustment to 0. In some micrometers there is a friction ring between sleeves 5 and 6 which prevents the screw being forced against the object with not more than a definite pressure, and turns freely after such force is applied. Skilled observers, however, certainly work as accurately by touch of the hand as with this friction device.

If the thickness of soft bodies is to be measured, the ends 2 and 3 are provided with shoes which provide large contact-surfaces to prevent crushing (paper, leather, cloth, etc.).

667. For some purposes it is convenient to use a light electric current to indicate contact, because great sensitiveness is obtained thereby (*L 215*, p. 21, Fig. 1).

I constructed the micrometer apparatus based on this principle shown by Fig. 444 for the Charlottenburg Laboratory. The apparatus served to determine the changes of length of blocks of concrete of different mixtures during continuous hardening and under thermal changes. The brass pipe 5 was rammed into the concrete block 8 × 8 × 30 in.

(20 × 20 × 75 cm), Fig. 445, by means of a brass disk; otherwise the pipe was quite free in the concrete, as the sleeve surrounding the pipe was withdrawn immediately after completion. The brass pegs 2 were built into the block by a special templet which insured their identical position in all. Pegs 2 had spherical heads which supported a disk of plate glass 1, about 0.6 in. (15 mm) thick, on which the micrometer-screw 3, Fig. 444, was mounted. The gauge 6 is notched at each end, both edges of one notch bearing against one pin, 2, the other bearing against the other pin. The third pin, 2, merely supports the plate. In this manner the disk was always replaced in exactly the same position for each measurement, and the micrometer-point 3 was sure to invariably touch the same point of the end surface of tube 5, because it was secured in one position by three wooden wedges inserted in the space at the upper end. The micrometer was connected with the weak current of a galvanoscope. The other wire was connected with the brass tube. The contact of micrometer and brass tube was clearly marked. In order to detect any changes of the instrument, especially of the point of micrometer, the apparatus was placed on a cast-iron gauge-plate provided with three supporting pins similar to those in the concrete, after each series of tests, and carefully preserved. Table 45 gives a series of calibration measurements on this gauge-plate which prove that adjustment by use of electric contact has a probable error of $0.64 \cdot \frac{1}{2000}$. The head of the micrometer is divided into 100 parts, and the screw has two threads per millimeter.

668. Bauschinger introduced a sensitive micrometer with contact-lever for measuring changes of length of cement and mortar during setting, in 1878, Fig. 446 (*L 2*, Part 8). The stand 1 carries a micrometer 3 by the lever 5 and a very easily movable suspension-rod 4. The test-piece 2, about 4 in. (100 mm) long, and having contact-plates at its ends, is supported on a firm table on 1. The point of contact-lever 10 is brought to bear against one end of the bar, and micrometer

7 is then turned until 10 coincides with the mark 11. The screw has 2 threads per mm, and the head is divided into 100 parts, and its revolutions are indicated on 8. The balance-weight 13 maintains contact. The spring 12 insures a constant pressure against the end of micrometer-screw. The instrument has been made in large numbers by Bauschinger's assistant, Klebe of Munich.

Table 45. Calibration-readings of an Electric-contact Spherometer.

Series I and II were made indoors; III and IV in the open air, after exposure of 1 hour; during readings I and II and III and IV the instrument remained on the plate.

Value of divisions $\frac{1}{1000}$ mm.

	9/1/95 I 21.50° C.	9/1/95 II 21.5° C.	9/1/95 III − 1.0° C.	9/1/95 IV − 1.0° C.	12/1/95 V 19.0° C.	14/1/95 VI 16.5° C.
	13355	13351	13349	13348	13351	13350
	5	2	8	8	1	0
	4	4	8	6	0	0
	3	3	9	7	1	49
	2	4	7	6	1	51
	2	4	5	8	1	49
	4	4	6	8	1	50
	3	3	7	8	1	0
	5	2	7	8	0	0
	4	1	6	8	0	0
Mean	53.7	52.8	47.2	47.5	50.7	49.9
$r = \pm$	0.78	0.83	0.89	0.57	0.33	0.38

r from all readings (60) = ± 0.64.

I constructed an apparatus for the same purpose for the Charlottenburg Laboratory, by which the changes of length of 10 test-pieces were determined simultaneously by photographic means, without again touching them after being placed in position. I used contact-levers 4, after the method of Debray, Paris, which remain in permanent contact with the test-pieces 3, as shown in Fig. 447. The levers 4, having a knife-edge 0.08 in. (2 mm) long, bear on the body 3, and two other knife-edges, in the same line, and each also 0.08 in. long, bear in grooves of the frame 1. This holds the upper end of the bodies very accurately in one position without constraint,

their lower ends resting on the adjusting-screws 2. The end of the contact-lever is blackened, and moves over the mm scale 5 without touching it. The lever-ratio is 1:20; hence the changes of length may be estimated to about the $\frac{1}{5000}$ in. ($\frac{1}{200}$ mm). Ten test-pieces are mounted in a frame, and three frames stand on one glass plate, one behind the other, each having three feet. This plate may be very readily immersed in a bath by means of long handles, and supported on a wall-bracket free from vibrations. The bath permits replenishing the water without vibrations. The readings are obtained by photographing the three scales placed behind each other and after developing the plate. The multiplication may easily be made 50-fold without modifying the construction; by applying the principle of my mirror apparatus (*692–699*) 100- or even 200-fold reading may be easily obtained without otherwise changing the method described. 20-fold magnification will suffice for determining swelling of bond materials.

669. Adopting B a u s c h i n g e r ' s construction of sensitive micrometer, K l e b e constructed an apparatus, Fig. 448, for measuring thickness. This apparatus is used at the C h a r l o t t e n b u r g L a b o r a t o r y, especially for regularly calibrating the B a u s c h i n g e r (*690* and *691*) and M a r t e n s (*692–699*) mirror apparatus, as well as other instruments of precision. The contact-lever 5 is delicately supported on the frame 2, and can be raised or lowered by screw 4. The number of revolutions made by the micrometer-screw 6, having 5 threads per mm, are counted by the wheel 8. The contact-levers 14 and 15 indicate the adjustment on scale 16. This scale, added upon my suggestion, increases the accuracy of readings materially. For the purpose of measuring thicknesses (say of roller of B a u s c h i n g e r mirror apparatus) it is only necessary to adjust the micrometer approximately, and the last figures of reading may then be obtained from the index-scale 16 by taking that reading as the reading of initial

adjustment at which the contact-lever reverses its original motion when the screw 4 is turned further. The positive or negative value of reading on 16 in terms of revolutions R of micrometer is added to the reading of the latter. The value of the scale-divisions were determined by measurements; it is as a mean:

$$1 \text{ division} = (10.75 \pm 0.04)\, R\, 10^{-4}$$

for the Charlottenburg apparatus.

It appeared very desirable that at least the largest public testing laboratories in Germany at that time might obtain concurrent results. In order to obtain this condition the Klebe-Bauschinger apparatus was procured, and then Bauschinger and the Charlottenburg Laboratory, at my request, made a very careful comparison of their two instruments by measuring the same body, previously measured by the Standards Calibrating Commission at Berlin, at different temperatures, in order to determine the factors of expansion by heat of the instruments, at the same time. A standard such as is shown in Fig. 449*a*, of steel, was selected for this purpose, the central hardened part of which had a middle zone 4 mm wide marked on it. Two diameters midway between these rings and at right angles to each other, passing through planes indicated by lines 1 and 2 on the right end of the piece, are measured. These two diameters were found to be:

Diameter.	Standards Calibrating Commission. *a*	Bauschinger. *b*	Charlottenburg Laboratory. *c*	Ratio. *a/c*
1—3	9.9830	10.07898	9.97238	1.00106
2—4	9.9822	10.07813	9.97152	1.00107
Difference.	0.0008	0.00085	0.00086	—
Mean.......	9.9826	10.07856	9.97195	**1.001065**

Hence measurements made by the apparatus calculated for a temperature of 20° C. (71° F.) should be multiplied by 1.001065 in order to give the correct result in millimeters.

B. Measurement of Deformations during Test.

670. Having discussed several recurring devices in measuring-instruments, and several arrangements used for definite purposes, those instruments which are used for measuring changes of length during test shall be discussed.

a. Reading-scales, Indicating-levers, Pivoted and Friction Rollers.

671. Several simple scales have been described in (*76*), and in (*137*) methods for determining extension after rupture are discussed. In (*156*, *b*) the method introduced by myself in the Charlottenburg Testing Laboratory, in which the divisions are marked according to the value $l_4 = 0.565 \sqrt{a}$, and the scales divided into per cents of gauge-lengths, are described. I again desire briefly to call attention to the advantage thereby obtained, without entering upon the description of the simple reading-scales.

672. Although personally I attach little practical value in general to efforts to be able to read or indicate measurements of extension with slight magnification, I shall nevertheless mention a few devices, because others are of a different opinion.

I shall omit the vernier, and merely mention that very long verniers are used by some, provided with lenses, to be able to read to about $\frac{1}{50}$ mm (0.002 in.).

673. A vernier in connection with a multiplying-lever, designed by the late Col. W. H. Paine, is sold by Riehlé Bros. of Philadelphia, Pa., Fig. 449*b*. The instruments consist of two slides which are attached to the gauge-marks by points and clamping-springs at either end. The left slide is provided with a scale, while the other has a

vernier for direct readings (to $\frac{1}{10000}$ in.-0.0025 mm). The multiplying-lever hangs on a pin at the upper end of the right-hand slide, its short arm being moved by a block on the left slide, while the long arm pushes a vernier over a scale. The lever multiplies about 20 times, and the readings on the vernier are $\frac{1}{10000}$ in. This, however, requires a magnifying-glass. The instrument measures but one element of the bar; its accuracy depends upon that of the scale, the ratio of lever, the error of angularity of lever ($90° \pm \Delta\alpha$), the lost motion at centre of motion, flexure of the long lever produced by the friction of the sliding vernier. It must also be certain that the block on the right-hand slide is truly plane, and normal to the direction of motion, if it is not to be a source of error.

674. The extensometer of Prof. Kennedy, London, is shown diagrammatically in Fig. 450. It consists of a bar, 2, held against test-piece 1 by a clamping-spring, 5, a multiplying-lever, 3, being carried by pivots on the upper end of 2, indicating extensions on the scale 4. The ratio may easily be $\frac{1}{50}$ or $\frac{1}{100}$, and $\frac{1}{500}$ or $\frac{1}{1000}$ mm may be estimated on an arc divided into millimeters. As the instrument is simple and can be securely attached, reliable results may be expected. Flexure of 2 produced by spring 5 may of course affect adjustment, as it is transmitted to the scale; but as the variations of the stress in the apparatus during test are immaterial, readings are hardlyaffected thereby. Theoretical and instrumental errors may be calculated or determined by calibration, and corrections applied from tables of errors, as the initial position of the lever is fixed by the o of scale (*89*). The apparatus certainly deserves serious consideration. Pivoting the lever 3 is questionable, and its results are probably dependent upon accuracy of workmanship; but a conscientious observer will certainly determine the errors of his instruments in every case.

675. By successfully applying the principles of my mirror apparatus to the Kennedy apparatus it has taken the form

shown by Fig. 451, in which it has been built for the Charlottenburg Laboratory and others by the laboratory mechanic E. Boehme. It was my object to take from it its spreading appearance, by attaching the scales to the lower end of the gauge-bars 2. The arrangement will be understood from (*88*) and the drawing. The statements regarding sources of errors in (*674*) also apply in this case. An examination of the accuracy of the instruments based on Kennedy's principle leads to the following. In material having a factor of extension $e_f = 5 . 10^{-7}$ for $\Delta S = 100$ at., and for $l_e = 8$ in. (20 cm),

$$e_1 = Se_f \cdot l_e = 100 . 20 . 5 . 10^{-7} = \tfrac{1}{1000} \text{ cm},$$

or 0.01 mm, i.e., in a single apparatus = 10 units of estimations (or vernier), and in a duplex apparatus together 20 units, in which errors of readings of $\pm$ 2 units may be estimated. If the *P*-limit (*37*) be assumed very high, $S_P = 42{,}660$ lbs. (= 3000 at.), the scale would be 1.2 in. (30 mm) long; 2.0 in. (50 mm) will therefore always suffice. As a rule the instruments are made for shorter lengths l_e, because it is inconvenient to work with such long test-pieces as required for $l_e = 8$ in. (20 cm). Therefore the scale is more finely divided, and the multiplying ratio is modified.

676. Klebe, Munich, constructed a lever apparatus, inspired by a publication of Debray, Paris (*L 253*), having multiplication of 2. From this Bach, Stuttgart, had an apparatus constructed shown in Fig. 452. He dropped the geared transmission of motion of his predecessors, and used a metal band instead (*547* and *548*). Fig. 452 shows the apparatus used by Bach (*L 27*, 1895, p. 491) for crushing-tests of blocks of concrete of $l_e = 30$ in. (75 cm). The two measuring-apparatus are placed in the same meridian plane on opposite sides of the test-pieces 1, and secured by 4 pointed screws in each of the frames 2 and 3. Frame 3 supports the double levers 6 and 7 and the graduated arc 8. The frame 2 carries the ad-

justing-screw 4, supporting the column 5, having a single- and a double-pointed end, and being made adjustable to any length l_e by the adjusting-screw 9. The column 5 acts on the lever 6, which (carried by pivots?) transmits the motion by thin metal bands to the pivoted rollers of the indicating-lever 7.

Regarding the probable degree of accuracy, and the sources of errors, I wish to refer briefly to the following, without laying claim to an exhaustive demonstration. The multiplication is stated to be 300-fold. If the arc be divided into millimeters, aside from the error due to the theory of the sine of angularity under increasing deformations, the readings might be estimated to $\frac{1}{3000}$ mm. The theoretical error may be eliminated by use of calculated tables of errors, but may be avoided by proper construction if the principle considered proper for connecting levers 6 and 7 by a metal band be applied at the short end of lever 6, rounding it off and attaching a thin metal band to it and the upper end of the column 5 (this band should be short because of the rapid adjustment to thermal changes). Whether, however, these wrapping connectors actually overcome the objections made by Bach against the use of friction in measuring-instruments (Bauschinger's roller-apparatus) can only be determined by accurate test (or calculation). Because of lack of data, it is difficult to say whether the stiffness of these connectors does not affect the ratio of multiplication. For the present it seems doubtful to me whether errors are not produced by the increasing and decreasing curvature of these bands when wrapping the arcs, especially during reversal of motion, i.e., during loading and release, similar to those produced by play, or slipping during transmission by friction. Great attention will certainly have to be paid to this point when it is a matter of absolute lengths and accuracy, and of determination of constants of elasticity, as well as to the possibility of lost motion in the pivot-bearings of levers caused by reversal of motion. Besides this there should be

considered what has been said in (*98*) about instruments used for the determination of the *P*-limit, and the question whether the apparatus works rapidly and with certainty; only those can form a judgment in this regard who have had practical experience with the apparatus. So as not to omit it, I wish to call attention to the fact that the point of support of lower end of column 5 should lie in the plane of the attaching screws in frames 2. The point of revolution of lever 6 meets this requirement.

As large lever-ratios are easily obtainable with a single lever, compound-lever systems should, if possible, be dispensed with in measuring-instruments. I wish to refer to an example of such construction by mentioning that of R. Fuess, Steglitz, who obtains a ratio of 1 : 1000 in the manner shown by Fig. 453. He constructs a lever consisting of two bevelled plates, 1 and 2, which are so arranged in the frame 5 that the edges lap by 0.0039 in. (0.1 mm). The supporting knife-edge 4 bears against the plate 1, and the movable fulcrum 3 against 2. A lever of but 4 in. (100 mm) length produces a multiplication of 1 : 1000.

677. The extensometer of Neel and Clermont (*L 18*, 1895, pp. 575 and 673) is shown in Figs. 454 and 455; the notation is the same in both figures. The springs 6, made adjustable by bolts 13, are attached to upper gauge-mark of length l, by the pointed screws 7. A frame is attached at the lower gauge-mark by pointed screws 3. This frame forms a lever, the end 2 of which is connected to lever 6 by pointed screws, while the other end, 4, is attached by pointed screws to a frame, forming the indicating-lever 5, connected at its short end by pointed screws 1 with spring 6. Hence the pointer 5 indicates the changes of length of l, in a multiplied manner, recording the motion of its point on a plate 9 revolving about its point of support. The scale is balanced by adding weights, and the lever 12 makes contact at 11; the electromagnet 10 then revolves 9 slightly, the point leaving a trace. The distance between marks indicates changes of length of l, for each interval of load.

This apparatus, in my opinion, received extravagant praise

in the reference stated, which led me to publish the following criticism:

The idea of obtaining a record is undoubtedly bright and singular, although it is not quite without predecessors. As a recorder, it must be compared with simpler and more practical designs, among which, without referring to mirror apparatus, I will name the recorders of Unwin and Kennedy; the latter may be materially improved when used as a reading-apparatus (*675*). The ratio of multiplication of the recorder, the constant C, assuming that the lever $23 = 34 = c$ and the length of indicator $= b$, is given as $C = \frac{2b}{a} = \frac{500}{1}$. The length of lever $14 = a$ would hence be 1 mm when using a pointer 250 mm long, or a practicable length. It may be urged against the general principle of the extension-indicator that the extension measured on arc 9, Fig. 454, requires recalculation if accurate values are desired; this can, however, be done readily by tables and is of little importance. The objections urged from the practical point of actual testing are much more important.

The writer does not state where the plate 9 is supported; and this is essential. Notable errors may arise when it is not supported on the test-piece, and then at the gauge-marks, otherwise shifting of the gauge-marks in space will be recorded as well. This objection is a matter of principle if the supposition to be drawn from the description, but not positively proved, is correct.

In opposition to the writer I cannot consider the principle of construction of this recorder as either skilful or worthy of imitation. I am, moreover, convinced that a calibration of the apparatus will readily prove its insufficiency as a measuring-instrument. If, however, the apparatus is to be used only as a recorder, then the determination of the factor of extension $\left(e_f = \frac{1}{E}\right)$ from the diagram is inadmissible because inaccurate. Even for this purpose the instrument is very clumsy, as will be seen from the following:

Apparently the apparatus is intended for but one case alone, that of a test of a square bar of about 0.8 in. face (20 mm) (it may be applicable to a round bar of same diameter, but its difficulty of attachment is greater); it also seems to be constructed only for a length $l_e = 8$ in. (200 mm), at least provisions for shortening the side springs are not noticeable.

No explanation of its method of attachment to test-pieces is given. But, according to Fig. 455, it cannot be attached to shouldered test-pieces without at least taking the lower frame apart. The constructor seems to admit this by providing the pointed screws with broad (knurled?) heads. How, in fact, can an apparatus work accurately in which lever-motions depend upon four pair of pointed screws, of which generally two (the clamping-screws 3) must each

time be loosened, and reinserted into rough punch-marks, or even forced into the test-piece? The screws 3 must be forced with sufficient pressure to spring the frames, in order that they remain in position on the test-piece during a diminution of section, otherwise accuracy is impossible. If, however, the screws 3 are always forced in an uncontrollable manner, so that the frame, acting as their nuts, is sprung outwardly, the pointed screws of the indicating-lever must always suffer an indefinite increase of pressure; what becomes of the permanence of lever-ratios in such case, and the constancy of frictional resistances? And furthermore, what will happen when it is necessary to dismantle the apparatus each time a test-piece is to be inserted in it? The springs 6 are spread laterally by rollers 8 bearing between them and the test-piece, and strain the pointed screws in the direction of the double-headed arrows (Fig, 454) differently during test. The stress produced by the rollers is different in each test. What will happen if the work necessary for proper attachment is to be done at a steel-works?

But this does not complete my objections. It is generally considered necessary to measure elastic deformations on two opposite elements of a test-piece in order to obtain the mean extension even approximately (it is not possible to do this accurately because the inner elements undergo different extension from those on the surface, which alone are measurable). There are, however, apparatus which avoid the separate measurement of extension of two elements, and attempt the direct reading of the mean extension by means of mechanical devices [Unwin (*704*), Hartig (*703*), etc.]; to these belongs that of Neel-Clermont. Although the solution of this problem is technically difficult as long as accurate readings are desired, and must thus far be considered generally questionable, it should be remarked about the above-discussed apparatus that it solves this problem in a very unfortunate manner. (I am certain that an accurate investigation of the sources of errors will justify this, my opinion derived from an examination of the drawings.) This will seem clear when it is noted that the upper clamping-screws are set at R.A. to the lower pair. It is simply impossible, even when making the gauge-marks in a special device, to attach this recorder in such manner that the upper part does not exert stress on the lower, i. e., primarily on the screw-points of the levers; what becomes in such case of the accuracy of indications? The principle has been established (as previously stated) of measuring the extension of two fibres; this has only been done because it is known that both fibres frequently stretch differently. When this happens there must be constraint on the pivots of the levers, and the uncontrollable effect on the degree of accuracy may also arise if the apparatus had been originally applied in a perfect manner.

Securing the springs at the upper ends by pivot-screws is also questionable, because it is not invariably safe under all circumstances. The screws must be forced so hard as to fill the holes in

the springs completely ; and the points must also fit into the punch-marks. Screws 13 of course provide for rough initial adjustment of the pointer, but it is not shown how the pointer can be accurately adjusted to the smoked-glass plate.

I have here indicated the objections noticeable from the illustrations only hastily, and cannot enter upon closer discussion of the sources of errors which must be due to workmanship in such constructions ; it is merely necessary to think of the effects of eccentricity of screws to realize the possibilities.

The Neel-Clermont apparatus cannot lay claim to being an unobjectionable measuring-instrument, as I have shown; it might only serve as a diagramming-apparatus of interesting construction based on noteworthy principles, but before using it for measurements it would certainly be necessary to calibrate each instrument and before each test.

678. The following apparatus should also be classified with that discussed in (*670–677*):

(*77*) Bauschinger's roller, apparatus [when used with string, *193*, Fig. 136; *204*, Fig. 150].

(*192*) Bauschinger's contact-levers for thrust-tests (Fig. 135).

(*194*) Martens, records with Bauschinger contact-lever, thrust-tests (Fig. 137).

(*195*) Engineering Laboratory, M. I. T., Boston, recorder for thrust-tests (Fig. 138).

(*421*) Martens, measurements of circumferential changes of vessels under hydraulic pressure-test (Fig. 292).

(*532*) Martens, load-indicator for the Pohlmeyer machine (Pl. 9, Figs. 19–27.) (Discussion of errors, see *534 a–e*.)

(*543*) Wendler, stress- and strain-indicator.

(*544*, *545*, *548*, *549*) Leuner's devices for measuring stress and strain.

679. With special regard to the statement relative to errors of wrapping connectors (*534*, *k*), I desire to call attention to the skilful arrangement in the apparatus of G. Boley, Esslingen, which Bach describes (L *27*, 1890, p. 1042). He uses a V-shaped thin forked metal strip 1, Fig. 456, which

wraps itself spirally about the axis of the indicator. This permits several revolutions without errors, as stated in (*534*); possible errors due to rigidity of connector still remain (*676*).

679a. Another extensometer with wrapping connector is that of Henning, 1884, shown by Fig. 456a. It consists of a large divided circle, *C*, 10 in. diam., having a hub, *H*, 1 in. diam., mounted on a fram,e *A*, clamped to a telescopic rod (not shown), one end of which is attached to the test-piece at the gauge-mark by a centre-punch held in place by a spring-clamp. The other end of the rod slides in a post, *D*, secured to the other gauge-mark, held in place in a similar manner by punch at *G* and a clamp. A thin steel tape, *T*, is wrapped around the small hub *H*, its free end being clamped to the post *D*. As the material under test changes its length the rod slides in the post, and the circle at the same time revolves above a vernier, *V*, being actuated either by the tension of the tape or by a spring in the spring-case if the tension is released. The vernier-readings can be calibrated by a micrometer mounted on the post at *S*.

It will be noticed that this instrument measures deformations on one side of test-pieces only; that the tape is some distance above the surface of the material; and that it has some other minor sources of errors.* As it is generally used on long members, bridge members, eyebars, struts and columns, these errors are of minor importance, and can be eliminated by corrective tables deduced by calibration of each finished instrument. It has been found very handy and has given uniformly good results. The instrument reads to $\frac{1}{10000}$ in. (Added by G. C. Hg.).

680. The very old method of measuring by friction rollers with a multiplying indicating-lever (*77* and *677*), which has been made prominent by Bauschinger, deserves much greater attention, because of its simplicity and certainty of

* See (*L 44*, 1886).

measurements, than has been generally bestowed upon it by professional men. Changes of length between two points can be readily made to 0.01 mm estimation (= 0.00039 in.). It is in fact possible to make finer measurements if gauge-lengths are determined accurately, measuring on several elements if possible, and using smaller rollers.

A method of such demarcation of gauge-length in crushing or thrust-test is shown by Fig. 457. The supports 2 and 3 for knife-edge and roller bear in the gauge-marks *l*, by means of fine knife-edges at one end, the other having rollers bearing on the test-piece; this insures that the supports follow the relative motion of gauge-marks accurately, converting it by means of bar 4 into rotary motion of roller 3 carrying indicator 5. I have had similar supports made for the 500-ton Hoppe machine (*591–597*), which, serving as supports for rollers and scales, may also carry apparatus, as shown by Fig. 458. In these I have used rollers of 2 mm (= 0.078 in.) diam., and provided such scales that 0.01 mm (= 0.00039 in.) can be read by two opposite verniers. Double vernier readings eliminate eccentricity of scales.

681. In the apparatus thus far discussed the axis of roller was always pivoted or supported in journals. Extensometers, as shown in Fig. 459, have, however, been constructed in which the roller 1 is freely supported between two springs 2 and 3, by friction alone. In this manner exceedingly delicate, although crude, measuring-instruments may be constructed by use of a piece of fine steel wire and a grass haulm (stalk). A wire of 0.5 mm. diam. and an indicator 500 mm (20 in.) length give a multiplication of 1000. Such crude means are very useful occasionally. Stromeyer's extensometer is based on the principle shown by Fig. 459; he occasionally used wires of 0.1 mm (= 0.0039 in.) diam. as rollers. In apparatus having free rollers, as in Fig. 459, but one half of the relative displacement of gauge-

marks is magnified, and this fact should not be overlooked.

682. If the connecting-springs, as 2 and 3 in Fig. 459, are firmly connected to rollers by metal bands or strings (*676*, Fig. 452), a very reliable apparatus is obtained. It is, however, possible to use nothing but rollers and strings, the rollers running freely without gudgeons or pivots, as shown diagrammatically by Fig. 460. The roller is revolved by the pair of strings 2 and 3 very reliably, and held in its position, the stress in the strings being produced by the spiral springs shown at either end attached to sheaves 8 and 9. The only cause of motion of roller 1 is the relative displacement of pegs 6 and 7. For accurate results two instruments should of course be used. It is probable that instruments constructed on this scheme will easily give useful results for practical purposes if other means are not available. From the experience obtained while using a stress-indicator on a Pohlmeyer machine I expect even very reliable results from a strain-indicator, as shown by Fig. 460, although it cannot be denied that the attachment of the reading-scale offers some difficulty; this is, however, not insurmountable. It is possible to attach a thin, graduated aluminum disk loosely to a pin turned on the end of 1, and then to merely guard against accidental displacement of scale during test, even when it travels with the roller in the direction of its motion. The graduated disk may also be attached rigidly to the roller 1, using a cross-hair mounted across the disk and parallel to the strings 2 and 3, instead of an indicator. If readings can be made photographically, it would require neither reading nor scale, as it is possible to obtain consecutive pictures by the use of rigidly mounted apparatus, and comparing them directly, at any time.

683. The Buzby extensometer shown by Fig. 461 is based on the principle shown by Fig. 459. In it the graduated disk is rigidly connected to the roller 1, while a cross-hair is mounted across a small mirror and the graduations parallel to

the axis of the test-piece to facilitate readings. The cross-hair is made to coincide with its image in the mirror, and thus obtains readings without parallax. The smallest readings are said to be $\frac{1}{1000}$ in. (= 0.025); tenths might be estimated. The instrument measures on one element only, and cannot at all be used on opposite elements, except if two observers be available. The disk loads the roller quite heavily and unilaterally. When used in vertical machines there is the objection that friction alone holds the roller in position. Vibrations reduce friction, and therefore variations of position are not provided for, and may easily produce rotary motion, thus affecting the results. It is very probable, from the foregoing reasons, that repeated variation of stress between two limits will constantly produce differences of readings, indicating that the transmission of motion is not reliable because of the effect of the weight of the roller and disk. It will hardly be possible to attach the clamping-frames with such accuracy that the two springs hold the roller between them with certainty; as a rule they will bear as shown by Fig. 462. It is attempted to avoid this difficulty, as in the following instrument, by placing all movable parts and the springs in a frame, but this produces constraint and friction, which must exert indeterminate effect on results of measurements.

684. Riehlé Bros., Philadelphia, also construct the extensometer shown by Fig. 463, based on the principle of the Buzby instrument. In this the fundamental principle of measuring extensions on opposite elements of the material is at least provided for. The instrument shown to me at the World's Fair in Chicago was very neatly constructed of aluminum. One roller of the instrument carries the graduated arc (instead of a disk), and the other the indicator, in shape of a vernier.* Two such arcs and verniers are used on the instru-

* The instruments shown by Figs. 461 and 463 have given so little satisfaction that they are no longer made, confirming Prof. Martens' opinion completely.—G. C. Hg.

ment, the two arcs mounted on one roller and the verniers on the other. The springs are so placed as to cause the rollers to revolve in opposite directions. Aside from the errors caused by the pressure of the springs, as in the Buzby, and aside from the existing considerable lateral loading of roller, there is the further disturbing circumstance that the two axes of rotation, although lying at the middle point of l, gauge-length, and hence should not change their relative position, are hardly ever found in one line initially, or remain so during test. Eccentricity of graduated arcs and verniers, as shown in sketch Fig. 464 on an exaggerated scale, will therefore invariably exist. If it is small, it will be unimportant; it will be eliminated by the double reading. Instead of reading $b'b'_1$, bb_1 will be read at beginning of eccentricity. In this the assumption is made, though rarely ever fulfilled, that there is no eccentricity of the two graduated arcs and of the verniers themselves with relation to their axes. As the arcs and verniers must be moved in their bearings when adjusting to differently dimensioned test-pieces, the eccentricity of the arcs must vary in different tests. This is at least a very undesirable condition, which affects the measurements in an indeterminate manner. An error due to great eccentricity is caused by obliquity of divisions of vernier to those of scale, thereby affecting the reliability of readings, or by separation of vernier and scale, as the readings are made at the surfaces in contact. The instrument is divided into $\frac{1}{1000}$ in., and permits readings of $\frac{1}{10000}$ in. by the verniers ($=0.0025$ mm). The readings require two observers, or that one observer travel around the machine for each reading.

b. Extensometers with Micrometer-screws.

685. In spite of the inconveniences, repeatedly emphasized (*80*, *653–659*), connected with the use of micrometers for determining deformations in tests of materials, they still enjoy

widely extended use. They even seem to be preferred in some countries, as the following sections will show.*

It must be again emphasized that the considerations discussed in (*653–659*) should be carefully observed if reliable results are to be obtained by means of micrometers.

686. Riehlé Bros. construct the extensometer shown by Fig. 465. It consists of two stout metal rings secured to the center-punch marks on the test-piece by means of pointed screws. They are maintained in a position normal to the test-piece by two pairs of springs bearing against the latter; the distances between the planes of these rings are determined by means of micrometer end gauges after each application of load. Hence but one micrometer, shifted from side to side, is used. This causes the end gauge to extend under thermic changes, which amount to $l.\beta = 8 . 124 . 10^{-7} = 0.0001$ in. for each degree C. on an 8-in. gauge-length. If the micrometer reads to 0.001 and permits estimations of 0.0001 in., then 1° C. difference of temperature vitiates the estimated values. Sources of error besides the error of screw are the omission of spring-cushions on the clamping-screws (early loosening), and the fact that the points of contact do not lie in the planes of the screws. The possible error due to the latter cause may be neglected because of its small value, especially as material

* The preference of micrometers in the United States is due to the following facts. There were no instruments of precision in use in the United States for testing materials prior to 1884 except the Thurston micrometer and the Paine extensometer (*673*). The former was clumsy, difficult to adjust and inaccurate, and the latter was unreliable and had a very short range of unilateral readings, and hence a limited application. But when I constructed my double electric-contact micrometer, in 1884, and designed it so as to have a wide range of measurements and ready applicability to all ordinary sizes and shapes, it at once came into general use, being the only convenient available measuring-instrument. As my first double electric-contact micrometers were built by the Brown & Sharpe Co., Providence, R. I., they were mechanically very satisfactory. This caused their rapid general introduction, which was immediately followed by the production of many slightly modified forms, the first of which was designed by C. A. Marshall after he had seen and used mine.—G. C. Hg.

motion of the rings about their meridional plane in which measurements are made is precluded. The instrument cannot be called convenient, and it is deficient for accurate measurements.

687. Three other very similar instruments are used in the United States, which are successive modifications in the order named. Figs. 466 and 467 show the Henning micrometer, Fig. 468 the Marshall, and Fig. 469 the Yale. The Henning is made by Tinius Olsen & Co., the others by Riehlé Bros. The Henning was designed in 1883 and built in 1884.*

The electric contact is common to all, and was first used in tests of materials by Prof. R. H. Thurston, in 1875, in a very crudely designed instrument which was unsuitable. There are differences in detail, especially in the attaching-devices. All have clamping-frames with pointed screws without spring-cushions.† The instruments of Henning and of Marshall have, however, spring-cushions to steady the frames normally to the axis of bar. In the Yale a bar of rectangular section, to the left of the test-piece in Fig. 469, is supposed to maintain the frames in parallelism and at the same time adjust the instrument to the gauge-length and in position. In the Henning two hinged bars adjust the frames to gauge-length, which are removed after adjustment; both frames are openable for attaching. The others have open frames and are merely placed about the test-piece. Henning makes contact at the median plane, while the others make it nearer the plane of the lower frames.

The sources of errors, besides those of the screw previously mentioned, lie in the circumstance that, even in those instru-

* While designing this micrometer I discussed its original detail with C. A. Marshall, who was then Engineer of Tests of the Cambria Iron Co., Johnstown, Pa. As the instruments which I had built did not meet with his approval, he set to work to design a modification thereof, which was constructed two years later, in 1886.—G. C. Hg.

† The latest Henning micrometer has spring-cushioned clamping-points.

ments provided with steadying-devices, there must be shifting of the micrometer-points across the face of the contact-plug, and because of eccentricity of point, play of screw in the nut, and shifting of axes of contact-plugs relatively to those of micrometer-screws. The magnitude of the former depends upon accuracy of workmanship, but the latter also upon the properties of the material itself, in the case that opposite fibres to which the apparatus is attached extend unequally. In this case the two contact-planes must shift relatively to the contact-points, and defects in contact-surfaces will affect measurements.

688. If I were to adopt the use of micrometers, I would design them in a manner to avoid all constraint, about as shown in Fig. 470.

The frame 10 is attached to the lower gauge-marks on test-bar 1 by means of two pointed screws 11 and 12, the latter of which is spring-cushioned, permitting the ring to rotate on the points. The open frame 10 carries the contact-surfaces for the micrometers 4. The left-hand surface also carries a guide, 16, for the spherical end of 4. The right-hand contact-surface 13 is insulated by hard rubber, and is connected to the battery. The balance-weight 15 serves to keep the opposite surfaces in contact. A Cardani ring, 2 and 3, is attached at the upper gauge-marks by means of pointed screws 6 and 7, the latter being spring-cushioned, and carries the micrometers 4 and scales 5. Both rings forming the frame are open, so that the latter can be passed over the test-piece 1; they can be locked relatively to each other by the screw 9, to insure uniform initial adjustment. This is done after setting both micrometers 4 to 0; the screw 9 is then tightened, and separator 17 is placed between end of screw and the spring-case, being of such length that the point of 7 is withdrawn from the centre a distance equal to about one half diameter of test-piece; screw 6 is run back a similar distance. The upper part of the instrument may then be placed around the test-piece as a unit, so that the spherical ends of 4 stand on the contact-surfaces on frame 10. The upper frame is

then centred by the eye, and screw 6 advanced until its point and that of 7 bear against the test-piece; their points of contact may be enlarged by centre-punches. Hence the apparatus directly defines the end marks of gauge-length l_g. After screw 6 has been tightened sufficiently to cause 17 to drop out and the instrument is connected with bell and battery, it is ready for use. I prefer the galvanoscope with a needle striking a cork at the zero position to the annoying bell. During test within the yield-point the left-hand micrometer may be set roughly to approximately one half the elastic extension. This will cause the lower ring 10 to swing about points 11 and 12, and accurate adjustments are then made by one screw alone. The sum of both readings is noted. As the axis of revolution of 10 lies approximately in the plane of contacts, the adjustment of ring 10 does not affect the readings materially, and it is only necessary to see to it that the readings of both micrometers remain approximately alike. The position of the upper Cardani ring is accurately regulated by the guide 16, which is constructed in such manner that it cannot constrain the instrument even when opposite fibres do not elongate equally. Errors of gauge-length l_g are given directly by the initial reading; they may generally be disregarded or else easily allowed for. There are sources of errors in the action of the points of the attaching screws, but they can hardly amount to much, because they are under constant load, acting in the same direction.

689. Unwin has designed a very pretty type of micrometer-extensometer (*L 240*, p. 208), in which the errors of the American instruments are entirely avoided, but the work of measuring is made more difficult, as two levels and one micrometer must be read. The apparatus is based on the principles of Fig. 471. Levers 4 and 5 are attached by pointed screws 2 and 3 to the gauge-marks. The levers 4 and 5 carry the sensitive levels 6 and 7, and are separated by a micrometer 9 whose axis lies in the meridian plane of the test-piece and normal to the planes passing through gauge-marks 2–2 and 3–3,

the lever 5 being braced against the test-piece 1 by screw 8, so that the level 7 may be adjusted to zero. If the level 6 be brought to zero at the same time by the micrometer 9, the reading will be that of length of l_e (gauge-length) of the bar between the lines passing through 2–2 and 3–3 at the axis of bar. It must be presupposed that the axis of the micrometer always remains parallel to that of the bar as shown at *A*, Fig. 472. If the micrometer-rod be rigidly connected with lever 5 as drawn by Unwin (at R.A., as shown by dotted line at *B*, Fig. 472), the micrometer will of course measure the vertical distance between the two horizontal planes and their displacements, but these dimensions are identical with l_e and its changes only when l_e remains vertical. If otherwise, the micrometer-readings would have the further error due to shifting of point of contact. These must also occur when using a rigid connection, when line 2–2, Fig. 471, is bent during test. Although the sources of errors mentioned are not large, it seems to me to be more correct to provide ball joints at both ends of the micrometer-rod to allow constant adjustment to angular motions of l_e, and maintain parallelism, as indicated by full lines in Fig. 472, *B*. With such construction provision should of course be made to prevent the rods 9 from turning during observations. At any rate the Unwin micrometer may be somewhat inconvenient for practical use.

c. Mirror Apparatus.

690. Bauschinger may no doubt be designated as the one who by his progressive work established a well-merited reputation of the mirror apparatus for use in testing materials. By mirror apparatus convenience and minuteness of measurements have been brought to a state which has in no sense been obtainable by any of the instruments previously described. At the same time, by skilful use and careful determination of constants, great accuracy of measurements,

quite unattainable by the instruments previously described, may be reached.

691. Having already given a general description and the theory of Bauschinger's mirror apparatus (*81–86* and *90–98*), it will suffice to specially discuss the details of construction and to further dwell upon those errors caused by the instrument itself (the reader should refer to the sections named).

a. The first apparatus was designed by Bauschinger in 1873 and constructed by his assistant, the mechanic C. Klebe, in Munich, who still constructs and furnishes the instruments. I merely desire to refer to the instructive development of the apparatus as published by Bauschinger (*L 2*, *9* and *11* of different volumes), for which I express my best thanks to Mr. Klebe, who communicated them to me by correspondence, but shall confine myself to the construction of the instrument as finally adopted. It is shown on Pl. 3, Figs. 32–34, 3 and 18.

Both mirror apparatus to be used simultaneously are mounted on a frame similar to a parallel vise. Hence the two mirrors may be simultaneously clamped to the gauge-marks by means of knife-edges adjacent to the rollers. As the screw in the frame is 4 in. from the fulcra, it produces a considerable bending-moment in the mirror-brackets; the axes of mirrors do not remain parallel. The fulcra lie without the vertical plane passing through the clamping-screws; hence the mirror-support is subject to a torsional moment. The clamping-screw must be screwed home to safely clamp the apparatus, weighing 3.9 lbs. (1790 gr), to the test-piece when loaded up to the yield-point. In order to insure reliable clamping, and to minimize the deformation of frame, an auxiliary clamping-screw is provided in the slotted support, beside the axis of roller, in the instruments used at the Charlottenburg Testing Laboratory. The stresses previously mentioned, producing deformations which

are not readily determinable, should be avoided in measuring-instruments as a matter of principle, although the Bauschinger apparatus has furnished admirable results in spite of these defects. The axes of rollers are pivoted as at 1, Fig. 473, the pivots running in cylindrical holes about $\frac{1}{50}$ in. diam., the lower of which is supported by a spring, 3. The spring raises the spindle and insures a neat fit between the pivots and the edge formed by the conical and cylindrical holes; this avoids all play, and makes it possible to apply notable lateral pressure to the rollers 2 by means of the gauge-springs 4. To insure reliable friction between rollers 2 and gauge-springs 4 the latter are covered with the finest grade of emery-cloth, 5.

b. The rollers 2 generally consist of hard rubber. The Charlottenburg Laboratory has successfully used steel rollers, which had been provided in Prof. Spangenberg's time, to be able to use magnetized rollers.* The rollers of the mirror apparatus must be cylindrical and the surface concentric with axis. If this is not the case, the radius r (*82*) will vary, as well as the multiplication, according to the particular position of roller. It has been shown (*91*) that measurements of r must be accurately made to 0.000078 in. ($\frac{1}{5000}$ cm) (about $\frac{1}{10000}$ in.).

These measurements are made on a Bauschinger calibrator (*669*) provided with special devices for determining eccentricity. For this purpose the roller-spindles are pivoted in two blocks, precisely as in the mirror apparatus, but horizontally. At first the diameter of roller is measured at different points and in different directions by means of the indicator when free, whereupon the latter is adjusted and clamped to determine the eccentricity of roller while being revolved about its axis. The micrometer, Fig. 448, was backed off during the former. While revolving the roller, the indi-

* It might have been foreseen that magnetization would not produce beneficial results; nor were such obtained (see Table 46).

cator must move according to a definite law if eccentricity exists, its amount being readily determinable from the scale-readings.

c. It has been frequently questioned whether frictional transmission, as used by Bauschinger, is absolutely safe (*676*, Bach, *L 27*, 1895, p. 481). These doubts are justifiable under certain conditions (*683*, *684*). But in Bauschinger's apparatus the axes are vertical, and all weights of axis, etc., are transmitted to the pivots; hence torsional moments due to weight are minimal. Only impact and vibrations in the horizontal plane, or necessary very rapid motion of mirrors, may produce them. Another circumstance which might cause slip is the bearing of the pivots in their seats, of $\frac{1}{50}$ in. diam. It is a question, however, rather as to whether the roller will slip on the emery-paper when revolving, which would manifest itself during reversal of motion. I do not know whether this point has been specially investigated elsewhere; the Charlottenburg Laboratory has examined it conjointly with the calibration, but actual systematic examinations of this point have not been made. Further on will be found a series of measurements. It is in fact shown by extensive daily observations with some degree of certainty that such slip must be slight under ordinary conditions, and is not noticeable in routine work. The errors produced by other causes (thermic changes, stress in instrument, inaccuracy of rollers, inaccurate adjustment of scale, etc.) seem to outweigh the possible errors of slip very largely.

d. Notable errors may, however, arise when the axes of mirrors are oblique to the test-piece, in which case the motion of spring is no longer equatorial to the roller. According to Fig. 474 the error will be 1% for extension λ and roller-motion λ', and under an angle α between the axis and the vertical:

$$\cos \alpha = \frac{\lambda'}{\lambda} = \frac{0.99}{1.00}, \text{ or } \alpha = 8^\circ\ 6',$$

which is plainly visible to the naked eye. For ordinary con-

ditions and such obliquity the readings would have an error of 1.5 units (10^{-5} mm) and be too small.

e. An error which is occasionally very serious is produced by excessive deflection of weak gauge-springs, due to use of force in attaching, necessitated by applying ample pressure on rollers to insure positive motion. In such cases the assistants at the Charlottenburg Laboratory declare to have noticed an effect of 4 to 5 units with 150 units of readings for each increment of load. This error is produced as shown by Fig. 475. The curved spring assumes the angle α to the direction of motion (dotted line), and hence the circumferential displacement of roller will not be λ, but λ'. For readings of $\lambda = 150$ and $\lambda' = 155$ the angle α would be:

$$\cos \alpha = \frac{150}{155} \text{ or } \alpha = 14^\circ\ 35'.$$

This shows that it is incorrect to make the gauge-springs flexible and the clamping-frames rigid. The reverse condition should be recommended.

f. To present a survey of the magnitude of effect between roller and spring under unfavorable conditions, I shall present several series of tests in Table 46, which were obtained while examining a modified Bauschinger apparatus in 1890, although slip was not the special subject of investigation. The examination concerns an apparatus (*Ba*) with steel rollers and magnetic springs, procured by Spangenberg. The axes of this apparatus are not pivots but balls, Fig. 476; the lower bearing is not elastic but rigid, and the upper one is cut in an adjustable screw. Therefore it is exceedingly difficult to adjust the axes so as to avoid all lost motion, and the instrument is not as good as the Bauschinger type. The investigation was made by exchanging the springs without removing the roller axes of the Bauschinger apparatus (*Ba*) from the standard bar *OU*. This standard bar also had a Martens mirror apparatus (*Bc*) attached to it, which was left untouched, in order to thus obtain a direct comparison

of the effect of changes made in Ba. The results are tabulated in Table 46 A in the order in which they were obtained. To facilitate comparison, the results are tabulated in B according to results with the same springs, and in C the effect of adjustment of scale on readings is shown. The values in Table C are plotted in Fig. 477.

It will at once be seen from Table B that the conditions 1 to 5 of apparatus Ba give smaller readings than those of apparatus Bc, while the condition 6 produces the opposite result. Fig. 477, A, shows how the several groups of points are disposed about the line representing ratio $Ba/Bc = 1.00$; the circles represent condition 6. Following the values of extension of 9 t. as shown by Bc, it will be seen that there are variations from 1308 to 1323 units (cm 10^{-5}), omitting the last three values obtained under a different condition of the apparatus. The two means are, of $1–5 = 1315.9$ and $6 = 1317.0$. The mean value of these figures with relation to their relative importance will be

$$\frac{1315.9 \times 8 + 1317 \times 3}{11} = 1316.2;$$

the extremes vary from this value by $-8.2 = 0.62\%$ and $+6.8 = 0.52\%$. Under release of stress Bc invariably showed set of 1.5 or 3 units. These readings can be due only to thermal effects or to backlash in the instrument. It is difficult to decide which was the actual cause, as it is a question of difference of coefficients of expansion of bar OU and of the springs of apparatus Bc (which may be infinitely small) or of variations of thermal differences of bar OU and spring of B_c. As the temperature constantly rises during the morning in the laboratory, thermal differences must change constantly, but they were certainly very slight (in August). [From (*95*), a variation of $\frac{1}{20}°$ C. will amount to one unit of reading.] *

* In recent years the temperature of the laboratory is noted before and after every test when making important measurements. Material thus collected will readily permit determination of influence of heat. It is especially noticeable in winter, when overheated rooms must be aired.

Table 46.—Comparison of Mirror Apparatus with Standard Bar *OU* by Simultaneous Readings of Both Instruments.

Instruments used: Bauschinger with steel rollers $= Ba$; Martens $= Bc$ (V and VI). Both instruments attached to same bar. Werder machine, error = about 0.5%; observers, Rauh and Tingberg. Gauge-length = 15 cm.

A. Results of Tests.

Bar No. Date 1890. Time.	Load L. t	Total Extensions. Ba cm 10^{-6}	Bc cm 10^{-6}	Remarks to Ba.
OU				
19./8. 12^{10}	1	0	0	
	10	1282	1323	Springs with emery, moderately clamped.
	1	1	1.5	
12^{50}	1	0	0	
	10	1294	1317	Other springs with emery.
	1	7	0	
1^{30}	1	0	0	
	10	1294	1317	
	1	4	1.5	
2^{15}	1	0	0	
	2	151	148.5	Magnetic springs, without emery, slip
	1	4	0	down slowly; moderately clamped.
	6	805	733.5	
	1	320	1.5	
	1	0	0	
	10	1322	1315.5	Do; rigidly clamped, avoiding slip.
	1	7	1.5	
20./8. 9^{10}	1	0	0	Springs without emery; surface polished;
	10	1298	1317	left roller touches spring at a point.
	1	1	5	
9^{35}	1	0	0	
	10	1295	1318.5	Do; springs more carefully adjusted.
	1	3	1.5	
10^{0}	1	0	0	Magnetized springs adjusted with little
	10	1324	1317	care; short intervals; leaky piston.
	1	7	1.5	
11^{10}	1	0	0	
	10	1323	1317	
	1	4	1.5	
11^{55}	1	0	0	
	10	1288	1308	Springs polished at end.
	1	0	0	
12^{55}	1	0	0	
	10	1304	1311	Springs ground at end.
	1	4	1.5	
1^{40}	1	0	0	
	10	1295	1315.5	Do, and magnetized.
	1	−6	1.5	
2^{30}	1	0	—	
	10	1332	—	Magnetic springs.
	1	73	—	

Table 46.—*Continued.*

Bar No. Date 1890. Time.	Load L. t	Total Extension. Ba cm 10^{-5}	Bc cm 10^{-5}	Remarks to Ba.
OU 22./8. 10^{0}	1	0	0	Calibrated machine $\Delta P = -0.5\%$; springs as before; clamps in position C.
	10	1313	1312.5	
	1	0	1.5	
10^{15}	1	0	0	Do; clamps in position A.
	10	1312	1312.5	
	1	− 2	3	
10^{30}	1	0	0	Do; clamps in position B.
	10	1312	1311	
	1	0	3	

B. Comparison of Similar Conditions.

Type of Springs for Apparatus Ba.	Extensions for $\Delta L = 9t$. Ba cm 10^{-5}	Bc cm 10^{-5}	Permanent Set. Ba cm 10^{-5}	Bc cm 10^{-5}	Ba/Bc
Springs:					
1. With emery	1282	1323	1	1.5	0.9690
2. Without emery	1294	1317	7	0	9825
	1294	1317	4	1.5	9825
3. Ends polished	1298	1317	1	3	9856
	1295	1318.5	3	1.5	9822
	1288	1308	0	0	9847
4. Ends ground	1304	1311	4	1.5	9947
5. Ends ground and magnetized	1295	1315.5	−6	1.5	9844
Mean	1293.8	1315.9	—	—	0.9832
6. Magnetic 20./8.	1322	1315.5	7	1.5	1.0049
	1324	1318.5	7	1.5	0042
	1323	1317	4	1.5	0046
Mean	1323.0	1317.0	—	—	1.0046
Frame position C 22./8.	1313	1312.5	0	1.5	1.0004
" " A "	1312	1312.5	−2	3	0.9996
" " B "	1312	1311	0	3	1.0008
Mean	1312.3	1312.0	—	—	1.0004

Table 46.—*Continued.*

C. Effect of Adjustment of Level on Scale-beam on Reading *Ba*.

Adjustment of Level.	Load L. t	Extension in cm 10^{-6}	Remarks.
19./8. 1890			
Very low	3	354	Greatest difference, 6 units.
Accurate	3	356	
Slightly too high	3	360	
In first position	3	355	
Raised and accurate	3	357	
As usual	10	1351	5 units.
Raised, slightly too high	10	1354	
Piston leaking; sinking slightly too low	10	1349	

Examination of behavior of apparatus *Ba*, Table 46 B, while changing springs under conditions 1–5, shows variations of $-11.8 = 0.91\%$ and $10.2 = 0.79\%$ from the mean value 1293.8. In spite of these not too great differences, the relation between apparatus *Ba* and *Bc* seems to be much more largely affected, because the largest and smallest values are almost in contrast, hence giving the values 0.9690 and 0.9947, which do not, however, affect the average 0.9832 very materially.

Although the types of springs were considerably altered in the first group (conditions 1–5), passing from the rough (emery) to the smooth (highly polished) surfaces of contact, the values found for 9 t. do not seem to follow any law. Very probably the condition of stress in the spring, and especially the fact of weakness or stiffness of spring, is of greater importance than condition of contact-surfaces.

Although the readings of set after release are quite material in apparatus *Ba*, no law can be derived from them, especially as their number is insufficient. The results obtained under condition 6 especially warn against hasty conclusions, because those springs which apparently produce the greatest effect (the old magnetic Spangenberg springs) sometimes

show great final readings and then again small ones. Whether the striking differences of mutual behavior of apparatus *Ba* and *Bc* in the first and last groups of Table 46 B are due only to the springs cannot be decided from these reports alone. The attention of the apparatus will be found by comparison of the means of groups under condition 6 as follows:

$$\left.\begin{array}{r} \text{Apparatus } Ba\ \dfrac{1323.0}{1312.3} = 1.0081 \\ Bc\ \dfrac{1317.0}{1312.0} = 1.0038 \end{array}\right\} \text{Average } 0.6\ \%.$$

In the last group other radii of rollers were invariably used by pushing the springs back before each test, and then placing the frames into positions *A*, *B*, *C*; the effect is within the limits of accuracy of readings.

The results presented will readily show how necessary it is **to calibrate measuring-instruments as carefully as machines** if it is desired to obtain results which may lay claim to reliability.

g. I should like to call attention to another point in the Bauschinger mirror apparatus, not because it is of importance in the latter, but because of the principle which should be more closely observed in construction of mirror apparatus. The Bauschinger mirror (Fig. 478) is set in a metal frame, and movably pivoted by 6 in the frame 2. The adjusting-screw 3 is opposed by the spring 5. The metal frame expands differently from the glass, and may produce curvature of mirror, distortion of image and displacement, hence errors of readings. Mirrors should be so fixed in metal frames that distortion is impossible.* Screw 3 and spring 5, however, produce bending moments, and of two kinds. On one hand they tend to bend the mirror-frame about its axis $\overline{66}$

* The mirror-glass is very thick (about 3 mm) and probably merely puttied to the sides of the frames, so that direct distortions, as above indicated, are actually of no import in the Bauschinger apparatus; but in any case such construction should be avoided.

(this produces only scale-distortion and lack of definition of image if it is transmitted to the mirror proper). On the other hand, as pressure of both spring and screw are in the same direction, it tends to push the mirror bodily forward with relation to pivots 6; this may produce errors of readings if the mirror undergoes any curvature. [Translator's note. If the spring contact and screw 3 are not on the same line normal to axis $\overline{66}$ the mirror may also become warped.—G. C. Hg.] For the above reasons, the points of contact of spring and screw have been placed directly opposite each other on face and back of mirror on the medial line, in my and the Henning mirror apparatus, thus avoiding the possibility of distortion.

k. The Bauschinger mirror apparatus can be used for gauge-lengths down to 2 cm (= 0.8 in.) by using shorter springs and avoiding the above-mentioned errors. Failure to observe all the conditions may, however, lead to errors of measurements. This is, of course, much more important as gauge-length becomes less. Special attention is to be given to perfect contact of roller on pressure-frame.

If the spring is provided with a straight knife-edge as in *A*, Fig. 479, the supporting frame will cause the fulcra 2 to fit the surface of flat bar snugly as long as the pressure is applied at a point near the centre line of spring as indicated by the arrow 4. In this case the end of spring will not bear uniformly against the roller 3, in case its axis shifts from its correct position, without producing torsional stress in the springs; parallelism of roller axis and of knife-edge is, however, accidental. The roller would have a safe bearing if the knife-edge were replaced by a point as in *B*. In this case the supporting frame bearing at one point causes tilting of the spring, and introduces still more questionable uncertainties. The same would be true of a knife-edge bearing on a round bar, unless the method in *D* be adopted, by supporting at two points (two arrows 4), and preventing tilting. Case *B* might be arranged

similarly (see E), but this would again produce condition A. Naturally this is the case in D as well, as the line of contact of the bearing-points of the frame would have to be parallel to axis of rollers. The bearing of one body on two surfaces of other bodies each at two points is possible in but few instances, while bearing at two points on one body, and at a single point on the other, is possible in a great many cases. For this reason the spring of the Bauschinger apparatus should be constructed as in C, Fig. 479. This will insure bearing at two points on round (F) as well as on flat bars, and at one point of the roller, as shown by the dotted sections of test-pieces. Careful use and maintenance of apparatus would in this case also insure positive transmission of motion to the roller. If the matter is to be more complicated, the springs might be provided with surfaces adjusting themselves automatically to the rollers, again avoiding unnecessary support, previously described; but the increasing movable parts in measuring-apparatus always require very careful study.

692. The Martens mirror apparatus was designed in 1884, necessitated by using the Gauss' method on a vertical 50-ton Martens machine, while Bauschinger had perfected the method of measurements for a horizontal Werder machine. It was at the same time my object to construct as light an instrument as possible, having equal applicability with the Bauschinger form. My mirror apparatus, as well as other instruments originated in the Charlottenburg Laboratory, are constructed with admirable perfection by the Laboratory mechanic E. Boehme.

693. The earliest form of my mirror apparatus is described in (*L 162*); it is shown by Fig. 480. I merely refer to it, as it will be readily understood from the following description of the latest type, and merely wish to remark that I at first thought to materially facilitate its application, by rigidly connecting the

gauge-springs 2 by an elastic frame 4. Later experience developed the fact that it is much more practical to leave the several parts disconnected on principle, to insure absolute freedom from constraint.

694. The latest type of the Martens mirror apparatus is shown by Fig. 481 (*L 254, 255*). This apparatus weighs about $4\frac{1}{4}$ to $4\frac{1}{2}$ oz. (120–130 gr); all data relating to support and clamping of gauge-springs obtained during many years of practical experience have been embodied in this instrument, eliminating the error of initial adjustment as far as possible in accordance with discussion in (*89, a*), so that the error due to the difference between theory and approximate calculation (*89*) can be very readily corrected by tables, if this be considered necessary.

a. The bearing knife-edges no longer have an interrupted edge (Fig. 480, *A*); they have straight parallel edges, and can be more readily measured by the Bauschinger calibrator, using a special calibrating device designed by myself, and by a Zeiss screw-micrometer with object-table. In future the Zeiss spherometer will also be modified for such calibration. The mirror-frames 10 and 17 revolve readily on cylindrical spindles, secured against lateral displacement by a small set-screw engaging a fine groove; they are so well finished that it suffices to apply a thick lubricant (wax) to the spindles to prevent the frames from turning, as they are otherwise quite loose. The mirrors are made of truly plane parallel surfaces about 1 mm ($\frac{1}{25}$ in.) thick and the reflecting surface lies accurately in the axis of revolution of the knife-edges (in the edge bearing against the spring 2). This necessitates the use of two patterns for mirror-frames. Therefore the mirrors are marked with letters *V* and *H* (for front and rear mirror). The mirrors are supported by small pivots on the elastic arms 10 and 17 of the frames and fitting into holes drilled into the edges of the mirrors. The adjusting-screws 11 and 18 are counteracted by the light springs 12 and 19 without exerting

any bending moment on the mirrors. The balance-weights are provided with simple cylindrical pins about 25 mm (1 in.) long, or, still better, forked pointers, which indicate the initial position of knife-edges. This is done by setting the pins parallel, or, still better, by adjusting the pointer to one edge of the spring 2. As the angle β may be thus adjusted accurately to the fraction of a degree, the error as compared with $\beta = 0$ [Table 7, (*89*, *a*)] will be infinitely small; the residual error for $\beta = 0$ may, however, be taken from a table (*86*), and corrections readily applied. Of course the pointers 28 and 29 may be so placed that they will invariably adjust the knife-edges to the most favorable initial angle β (case II, *89*, *a*) initially.

The mirror-spindles are drawn as short as possible in Fig. 481; they may of course be made of any length, and it is proper to make them of such length that the distance between centres of mirrors corresponds to the relations between scales and telescopes, obviating great obliquity of mirrors to axes of revolutions.

b. In the new instruments as well, I have provided for contact of knife-edges at gauge-springs at two points, spring E (Fig. 481, B, D, F, G and H), while at the test-piece it bears at one point. The grooves in the forked spring E are first deeply filed as nearly as possible normal to the longitudial axis of the spring; their bottoms are then cut by the accurately ground edge of a cold-chisel, producing perfectly smooth and straight bearings for the mirror-fulcra, the angles of which are of course more considerable than those of the grooves in the springs.

It will be seen that the position of the axis of revolution of the mirrors at the springs is definitely fixed with relation to the spring. This produces an error which is constant, and which, if necessary, can be accurately determined. The position of the spring, parallel to axis of test-piece, is, as a rule, insured by the considerable length of the spring, and may be readily determined by the eye. It only becomes

necessary, therefore, to adjust the mirror-axes parallel to each other in a plane normal to axis of test-piece. This is done in the round bar by means of the clamping-spring 5. For this purpose I have shaped the other end of spring E into a knife-edge almost forming a point, Fig. 481, C, R–S. The spring 2 and the fulcra therefore bear against a round bar at two points only (both mirror apparatus in 4 points), separated by a distance $= l_g$. Because of this support of spring and fulcra at two points of the cylinder only, a tilting about the connecting line through the two points must naturally occur if it is not prevented. This is done without restraint by the clamping-spring 5.* It is simply bent out of a steel wire, and in such manner that both ends are as nearly parallel as possible. The ends bear in grooves on the bridges 3 and 4 as shown in Fig. 481, L to O, mounted on the gauge-springs, see A and B. Bridge 4 has two triangular grooves, in which the cylindrical end 5 of clamp-spring fits without constraint, thus fixing this spring in a definite position; it may still revolve about the axis of the wire until the other end of the spring drops into the groove of bridge 3, whereupon the gauge-spring connected to it revolves about the two points of support on the round test-bar until the straight back of bridge 3 is made to come in contact with the other cylindrical end of the clamp-spring 5. In this condition the whole is a rigid unit, in which all motion is prevented as long as the test-piece does not change its conditions of stress.

Attachment of the mirror apparatus to a flat bar changes the conditions of support, and hence the

* Boehme substitutes therefor a heavy clamp, Fig. 481a, of two slides, 1 and 2, drawn together by two spiral springs, 3, and separated by pressure of the hand on the end plates of the rods 1 and 2. The brackets 5 and 6 on these slides carry projections instead of spring 5, Fig. 481, L–O, which bear in the grooves of bridges 3 and 4. For flat bars pivots 4 are advanced and used as in Fig 481, E. This clamp works well and safely; but personally I prefer the simpler bent spring consisting of one piece.

action of clamp-spring 5 must be different, to avoid secondary stress in the apparatus; the spring should be provided with two points as in Fig. 481, *E*. In this case the fulcrum of the apparatus touches the test-piece on a line. (It would be best to make the edge of fulcrum slightly concave to and insure contact at two points.) In this case there is support at the test-bar in 3 points, and tilting is entirely avoided as long as the clamp-spring bears within the area bounded by lines drawn through the three supports. It is well to place the centre of pressure somewhat beyond the centre of the triangular area, toward the fixed point of spring 2. Each spring has one conical hole at this end. The points of clamp-spring 5 enter these holes. (See Fig. 481, *A* and *E*.) In this case a fixed unit is built up, which will move only when variations of stress are produced in the flat bar.

While the mirror-axes place themselves in parallel positions automatically, when attaching the apparatus to a round bar, provided the clamping-springs have once been properly bent, the position of the axes in case of a flat bar depends upon the conditions of the surface; if these be parallel, the axes will stand parallel.

c. Mirror apparatus are readily and quickly attached. The points of the gauge-springs 2 are placed in the upper gauge-marks, and the clamp-spring 5 is then made to straddle them. Then one spring is drawn back by means of the knob provided at its lower end, and the mirror-fulcrum is placed between the spring and the test-piece, having care that the indicator 28 or 29 coincides with the edge of spring. The same is done on the other side; the apparatus will be attached correctly to the gauge-length l_g on the test-piece, as the gauge-springs are of proper length to insure this. Their length may be made to suit any purpose, so that the springs provided with the apparatus adapt it to a great variety of purposes. The two knobs on the gauge-springs 2 have the purpose of preventing heating of the apparatus by the hands during adjustment.

In the old apparatus it was necessary to provide gauge-marks on the test-pieces, and then insert the fulcra in these marks, if the gauge-length was to be used with some reliability; this is avoided in the new apparatus. With the latter gauge-marks are entirely unnecessary, but it is always advisable to provide marks for the upper ends of springs; at their lower ends gauge-marks should not be provided for the new apparatus, if the reliability of observations is not to be disturbed. The mobility of mirror-fulcra in gauge-marks is always accompanied by accidental conditions, depending upon shape and character of the gauge-lines, and upon the accidental relative position of fulcra and of these lines.

d. After the apparatus is attached and the two telescopes are mounted on a firm tripod at an approximately correct distance, and in a position normal to the axes of the mirrors and in front of them, the scale-distances A (*88*, Fig. 46) from axes of mirrors are to be adjusted. This is most readily done by means of light wooden rods, cut about 1–1¼ in. less than distance A, and provided with thin cardboard to make up the exact length $= A$. This rod is butted horizontally against the scales mounted vertically, Fig. 482, moving the latter forward or back until the cardboard just reaches to the reflecting surface of mirrors, or to their outer surface if the card has been shortened to make allowance for the thickness of the glass.

The objectives are to be adjusted to the cross-hairs, and these are to be focussed on the centres of mirrors. Then the mirrors are adjusted about their vertical axis by an assistant (by screws 11 and 18, Fig. 481), until the proper scale is seen to be reflected in the mirror above the telescope. Then the telescope is focussed on the reflected scale, and the mirror revolved until the vertical cross-hair coincides with the centre of scale. The scale-reading is then stated to the assistant, who turns the mirror about its supporting axis, finally by very light tapping, until the desired initial reading is made to

almost agree with the horizontal cross-hair. The final adjustments of cross-hairs are made by the fine adjustments of the telescopes.

The whole work—gripping of test-piece, attaching mirrors, adjustment of mirrors and of telescopes, up to beginning of test--takes two skilled operators not more than four to six minutes.

What has here been stated about the application of my apparatus also applies to the Bauschinger apparatus, with due regard to special conditions.

695. The mirror apparatus just described have given admirable satisfaction at the Charlottenburg Laboratory during the last fourteen years, and at numerous other places. They have been used for most various purposes, and modified accordingly, as I have previously stated (*181*, Fig. 128; *206*, Fig. 153; *300*, Fig. 206). I wish to present a few other characteristic forms, because the limits of applicability of mirror-readings will be readily appreciated thereby.

696. Fig. 383 shows the arrangement of mirror apparatus which I have designed for the large 500-ton machine of the Charlottenburg Laboratory (Hoppe machine, Pl. 10). This apparatus (for very great gauge-lengths l_t up to several meters) is provided with gauge-springs in shape of wooden boxes, composed of pieces keyed together by means of wedges, 4. These tubes can be connected at one end to the mirror-support and at the other with the end fulcrum; it is supported on the large standard bar (*595*, *i*, Fig. 420) by means of the devices shown in Figs. *N* to *T*. The apparatus is designed in such manner that differences of extension for each increment of load are read on the same points of the scales and same positions of mirrors, that all errors of approximation to true theory have exactly the same value for each observation, and the values found are directly comparable without corrections even when mirror motions become very great.

For this purpose an arrangement was to be made whereby

the gauge-springs could be lengthened successively by the amount of extension due to each increment of load, i.e., that the mirror could always be adjusted to zero reading. This has been done in the following manner:

The mirror-support *H* to *L* consists of a brass bar 18, which has set-screws 19, 20 and 23 and springs 21 and 24, as well as the steel plate 27 supporting the fulcrum 25. Fulcra and mirrors 25 are shown at *K* and *N*. The fulcrum is bevelled at lower side so that its bearing edge bears against the steel plate 27 (see *N*) when the mirror is placed between springs 22 and 24. To do this the screw 19 is first advanced sufficiently to maintain 18 at a proper distance from the test-piece, after the long gauge-rods have been attached to their suspension device. The screw 23 is then advanced until spring 24 is quite clear of groove in 18. Then the spring 21 is spread by screw 20 just sufficiently to permit the mirror-fulcrum to be inserted in the grooves of the two springs, and remain there safely.

The two clamping-springs *U* 38, bearing at 18 (and at 13, *A* and *C*), are then made to bear lightly against the test-piece 1 by means of their spherical end knobs. By means of the suspension device *N* 36, 37 the apparatus is adjusted to correct height, etc., until fulcrum 11 (*A* to *C*) fits a mark on the bar 1. Thus the mirror-fulcrum is made to stand opposite the body 22 attached to the test-piece. If now the screw 20 be released, the mirror-fulcrum will bear firmly in the grooves of springs 21 and 24; it will therefore always assume the same initial position relative to bar 18 when the screw 23 is also released, causing the fulcrum to bear against 18. Now it is possible to secure contact of fulcrum and the curved bearing surface of 22 by releasing screw 19.

After adjusting the telescopes and scales for initial reading as in (*694*), the test may begin. After balancing the machine under the first load a reading is taken, and the mirrors are then returned to the initial reading by means of strings leading to

the position of the observer, and passing over a roller 12 driving a worm-gear 8 on the end of the fulcrum-spindle (A–E), so that the length of gauge-rod E is lengthened by means of micrometer-screw 5 by an amount equal to the extension of the standard bar. The micrometer is provided with a friction-coupling 6, by means of which the worm-gear 7 is disengaged from the micrometer. The screw can be moved rapidly by means of head 10 to bring the gauge-rod to its initial position after test. Scales are attached to the micrometer, which, however, are not used as a rule.

It will be readily seen that very fine measurements may be made by this apparatus, and it is in fact possible to measure extensions of the 6.32-in. (160-mm) standard bar due to a load of 45 lbs. (20 kg); i.e., by a stress $S = 1.42$ lbs. per sq. in. ($= 0.01$ kg. sq. mm).

The apparatus here described has served almost exclusively for measurements of the large standard bar of the 500-ton machine, and has given great satisfaction.

697. I have built another mirror apparatus, Figs. 484 and 485, for use in tests of very small pieces of material; it has a length of but $l_g = 0.4$ in. (1 cm), and is used mainly in pressure-tests (crushing-tests) in connection with the apparatus described in (*73*), Fig. 39; also shown by A and B, Fig. 484, as applied to the test-piece.

Its adjustment to correct gauge-length and attachment of mirror-supports are shown by Fig. 485. The gauge-springs consist of two odd-shaped parts, as shown diagrammatically in Fig. 486. The two parts are each provided with a gapped fulcrum which bears against the test-piece at two points; thereby each mirror apparatus bears on the test-piece at four points, hence in as perfect a manner as possible. Both parts of the gauge-spring are braced by each other and the mirror-fulcrum and a roller. The fulcrum and the roller are each supported in two points below and in one above. The parts are clamped together by means of two

spiral springs, which press the apparatus against the test-piece. The two parts, otherwise passing loosely through each other, may be connected before attachment by means of two conical pins with head, in such manner that the fulcra are separated by exactly 0.4 in. (= 1 cm). The instruments are therefore attached to the test-piece without scribing gauge-marks. The arrangement of mirrors is shown by Fig. 484, *C* to *E*.

The apparatus is usually used for estimated readings of .00000195 in. (= $\frac{1}{20000}$ mm). It has been found very reliable, as readings for load increments for equal values of $\epsilon\%$ fluctuate by at most 2 or 3 units, the same as is the case with other Martens and Bauschinger mirror apparatus.

698. The sketch given in Fig. 487 proves that the use of the Martens principle in designing mirror apparatus enables making measurements on gauge-lengths $l_g = 0$. The apparatus served to determine the thickness of a layer of lubricant existing under different pressures and varying temperatures. If it is desired to be independent of elastic distortion of bodies 1 and 2, it is necessary to make measurements directly at the two end or bearing surfaces between which the layer is formed. For this purpose a, so to say, negative fulcrum was used, a fork 3 of hardened steel, the bearing-edge a_2 of which in the recess in body 1 bears against the end surface of 2. The counterweight 4 causes the edge a_1 in the recess of body 2 to bear against the end surface of 1. The fork 3 carries the mirror in the usual manner, as shown by Fig. 206 (*300*), by means of a third fulcrum. Hence if the two end surfaces of 1 and 2 recede from each other, the tilting of 3 will be indicated by the mirror. The apparatus has been most successfully used for estimated values of 0.00000195 in. (= $\frac{1}{20000}$ mm).

699. The Martens mirror apparatus has been very successfully used at the Charlottenburg Laboratory for testing cubes of stone and concrete of all sizes as to their

elastic behavior, as shown schematically by Fig. 488. In order to attach mirror apparatus on large surfaces, so as to be able to determine deformations of given lengths in any direction, in direction of or crosswise to the direction of force applied, and at every part of the surface, small saddles 1, bent out of sheet steel, are attached to one gauge-mark. They bear at the gauge-mark by two sharp edges in one line, and a tail-piece braces them at a third point. The sharp edges produce greater friction than the tail, and hence must remain at the gauge-mark, while the material undergoes deformations between them, without affecting the position of the saddle. In order to secure the saddle in its position without clamping-springs, even on vertical surfaces, it may be sealed with a drop of wax or resin-putty at the bearing-edges. The gauge-springs 2, made of steel wire about $\frac{1}{4}$ in. (6 mm) thick, may then be made to bear with their round ends on the fulcra 3, the other being shaped into sharp forked ends. The apparatus may be secured to the material by rubber hose, bands, wire springs, etc., passed around both; or it may be simply loaded by weights when attached to horizontal surfaces. If necessary, the forked bearing-edge of gauge-spring may also be secured by a little wax. The Charlottenburg Laboratory has already tested knuckle-joints of granite, sandstone and concrete [cubes of about 70 cm (= $27\frac{1}{2}$ in.) edges with cylindrical bearing-ends] in the 500-ton machine, making simultaneous observations with ten instruments. If measurements are to be made on opposite faces of large blocks (concrete, etc.), the reading-telescopes must be mounted and served independently if the usual short mirror-spindles be used. When long mirror-spindles are used, as in Fig. 206 (*300*), they may be mounted on one side as before, but each spindle must then be directly supported. If the use of two instruments is unimportant, the distortions of the test-piece (torsion due to movable gripping-devices) may be determined even when using but one apparatus, by simultaneous reading

of a mirror rigidly attached to the test-piece, and may be made harmless by correcting the readings of deformation.

My type of mirror apparatus may also be readily used for determining internal changes of shape of bodies if a hole of about 0.4 in. (10 mm) diam. be provided in the body. In this case, two gauge-springs similar to those shown in Fig. 488 are provided for each mirror apparatus. The fulcra are pressed against the walls of the holes by means of springs mounted on the backs of the gauge-springs, and the mirror is then placed between the latter as shown in Figs. 205 and 206 (*300*). The gauge-length is then equal to the distance between the bearing-edges of the gauge-springs. Figs. 205 and 206 show how mirror apparatus may be arranged when the gauge-marks are not directly accessible.

700. My 1884 mirror apparatus (*88*) has been modified in the two following instruments, in details which I cannot consider improvements, in so far as they do not embody the principle of reading by two independent telescropes, reading both mirrors by one only. Although the mirrors are placed so closely together that both scales appear in the field of view simultaneously, they are one behind the other a distance equal to the thickness of the bar, thus producing the difficulty of focussing the telescope with equal sharpness on both scales at the same time, i.e., that the images of the scales produced by the objective do not coincide exactly with the plane of the image of the cross-hairs. We therefore have the choice, firstly, either to focus both images imperfectly, i.e., to magnify the parallactic errors of both images (*694 d*), or, secondly, the eyepiece must be adjusted alternately for readings of the two scales, as stated by Kirsch (*L 23*, 1891, p. 139), or, thirdly, the distance of mirrors from scales may be corrected by one half the distance between mirrors, as personally explained to me by Kirsch, thus making the length of reflected rays from the cross-hairs to the scales equal to each other; in this case both instruments have different magnification. In the

first two cases the accuracy of readings is diminished, in the second one of the principal advantages of mirror-readings is discarded, namely that all parts of the apparatus remain untouched by the observer throughout a test. The third no doubt also has difficulties, for Kirsch informed me that he has abandoned the use of a single telescope and has reverted to the use of two.

701. The apparatus of Kirsch, Vienna (*L 23*, 1891, p. 139), and of Henning, New York, each have two mirror apparatus of my type with simultaneous readings by one telescope. The Kirsch mirror apparatus differs from mine only in that it has two points instead of a knife-edge at the end of the gauge-spring, which enter the gauge-mark on the flat as well as on the round bar. That this may be considered an ideal construction only conditionally will be evident from (*691, h*) and (*694, b*). Kirsch, as he told me personally, recognizing these conditions, made the points in the shape of adjustable pivots; I do not consider this an advantage, because this adds unnecessary movable parts to the gauge-spring. Kirsch also substituted transparent glass scales, illuminated by diffused light from a bright surface behind them. In this one is dependent upon the illumination of the laboratory; therefore the ground-glass scales commonly used in the Gauss' method of reading should be preferred, which may be readily illuminated by a number of small jets placed behind them.

702. The changes which Henning (*L 44*, 1897, May) made in my apparatus are shown by Figs. 489 and 491. They consist essentially in the provision for always obtaining uniform initial adjustment to gauge-length, distance between mirror-spindle and attaching-point. This is a very essential point, as becomes evident from the theory previously developed by me in (*88–98*) and the discussion presented in (*690–699*) relating to the principles which were my guides. This initial position is obtained by the little screws 19 supporting the

mirror-fulcra 12 in their frames 10 before attachment. Thus their position relative to gauge-springs 9 is predetermined accurately. The entire mirror apparatus is united by the bars 9, the upper end of which is cylindrical, on which the frame 10 swivels, bearing on a dished spring washer 11, against which it is pressed by the nut *S*, Fig. 489. Thus the mirror-axis may revolve about that of 9 in such manner that the fulcrum will bear accurately against the surface of any flat bar in every case. In case of round bars, however, there is unstable support of the fulcrum, because it is supported in only two points, in *a*, Fig. 492, at the bar, and at *b* on the axis of gauge-spring. Hence the tendency to tilt in direction of the double arrow will always exist. This tendency must always be counteracted by the elastic bending resistance of the gauge-springs, although their pressure on the test-bar at the same time assists it.

The construction of the mirror-fulcra resembles mine. But the attachment of the apparatus is different, as will be seen from Figs. 490 and 491. The frames 1 and 2 are hinged at bolts 3, one of which is removable. The frame is attached to the test-piece by the screws 4, which pass through spring-cushioned bushings, sliding in the frames and provided with springs 6. The points 5 also serve to carry the spring-carrier 7; they are screwed in to screws 4. The spring-carrier 7 has two lateral arms bearing on the frame, to prevent tilting. The gauge-springs 9 carrying the mirrors are bolted thereto.

The Henning mirror apparatus therefore forms a unit, which can be opened after removing pin 3 and then attached to the test-piece, without the necessity of marking off the gauge-length. Before attaching the apparatus the screws 8 are advanced as much as screws 4, thus keeping 7 in a vertical position, and always producing the same pressure of springs 9 on the fulcra; springs 9 are drawn back after closing the frame, and the fulcra, taking bearing on screws 19 and against

the test-piece, will remain in position; 19 are then loosened, and the mirrors are adjusted as in any apparatus.

No doubt the Henning apparatus may be attached more readily than mine. But I cannot be convinced that his construction is more perfect than mine with loose gauge-springs, for the advantages of simplicity and rigidity of principal parts, essential in my opinion, which excludes every uncontrollable secondary stress, and bases the entire attachment upon simple support of all parts on the test-bar among themselves, are lost. As measurements of 0.0000039 or 0.0000019 in. ($\frac{1}{1000000}$ or $\frac{1}{2000000}$ cm) are to be made, every connection which permits or may permit such minute motion during use is a source of uncertainty. Although I do not believe that there will be harmful changes in the connections of Henning's apparatus under careful manipulation during test, I consider it my duty to point out the fundamental deviations from the principles of the original construction, because these considerations are at the same time instructive.

703. Hartig (*L 9*, 1893, Part 6), starting from the simple apparatus furnished by Leuner with his machine having a standard bar (*549*), constructed a one-mirror apparatus, shown in Fig. 493. In this apparatus the evil of the old construction discussed in (*548*) (*L 9*, 1893, Part 6, Plate XIX), the use of one mirror placed distant from the test-piece, is avoided. Flexure of the test-piece must affect measurements; besides measurements were not made on a definite part of the prismatic bar of length l_r, but between clamps attached to the heads of the standard bar. The new apparatus avoids the errors due to flexure of bar and indefinite gauge-length.* The two frames 2 are attached by means of clamping-screws, each with three bearing-points in the end planes of the gauge-length l_r. The right-hand frame carries the cross-bars 17, to which the

* The straining-tapes 5 lie in the plane of the horizontal axis of test-piece, hence flexure in a vertical plane does not affect the result; bending in the horizontal plane is eliminated by the lever 7.

clamps 18 secure the very thin steel tapes 5 on a plane with the centre of the test-piece. These tapes 5 pass over small rollers mounted on a pivoted spindle 4, converting extension into rotary motion, and transmit the latter to the compensating beam 7 by means of the upper roller and tape 6. The beam 7 transmits the mean motion of 6 to the tape 8, which turns the mirror-axis 11. The mirror-mechanism is shown by Fig. 493.

The construction is very complicated, and the question is forced upon us whether the intended saving of one telescope and of the work required in duplex observations is not counterbalanced by the unprofitableness arising from the use of one mirror (*94, b*), as well as from the many points which are sources of errors; I call attention to the thin tapes, which must instantly respond to thermal changes. As I have not used the apparatus, I shall only refer to a few points which in my opinion should be examined. If the apparatus is to be used for absolute measurements (determination of E or $e\%$), its rate of multiplication must be determined accurately to begin with. This requires the determination of diameters and eccentricities of 5 rollers, and of the lengths of levers 7 (seven sources of error). Next, the effect of possible play of the three axes 4 and 11 in their bearings must be ascertained. As the axes run on fixed pivots [not in springs as in the Bauschinger apparatus (*691, a*, Fig. 473)], the play is dependent upon the adjustment of the pivots, and hence variable in a manner not easily controllable. How large the error of reading due to great eccentricity of the mirror may be, can be determined by calculation. In regard to construction of mirrors I refer to what has been said in (*691, g*), as well as to the effect of rigidity of the steel tapes in (*676*).

704. A single-mirror apparatus is shown schematically by Fig. 494; it has been constructed by Prof. W. C. Unwin, London, based on the principle described in (*689*). Fig. 471. Two stirrups, 2 and 3, are attached at a length $= l_1$ of the test-

bar 1 by means of pointed screws, 3 being adjustable normally to the bar by means of screw 4. The spreader 5 is fitted in punch-marks in 2 and 3, causing 2 to rotate about the supporting point on 5 whenever the bar 1 suffers deformation. This causes mirror 7 to rotate under action of spring 8. The rotation is read off by means of a telescope. The apparatus therefore measures the average deformation of two opposite elements, as the constant spreader 5 is placed in a meridian plane of the test-piece normal to the stirrup-pivots. If, as may be correctly assumed, the stirrup-pivots and ends of spreader 5, as well as the axis of revolution of the mirror-roller, lie in a plane, the different deformation of the elements measured cannot of course exert any material effect on the results of observations. If, however, the test-bar 1 bends, as indicated by dotted line 1', Fig. 495, the stirrup 3, being affected thereby, must vitiate the mirror-reading. A level is mounted on 3 in the Unwin apparatus, which I saw at McGill University, Montreal, Can., to insure invariability of 3. In this case it would become necessary to take a level-reading for every observation when accurate measurements are desired, or at least in cases where mirror-readings are great. This would, however, certainly make observations very much more difficult, which suggests the question whether the use of two mirrors is not finally more practical, especially when considering what has been said in (*94*, *b*) in relation to the effects of using one mirror.*

Without examining the theory of the instrument more closely, the sketch in Fig. 495 will readily show that it is very complicated. I drew the relative deformations of movable parts on an exaggerated scale for the case in which bar 1 suffers a material extension; the new position is indicated by dotted lines similarly lettered with indices. It will be clear

* This necessary occasional adjustment of level would moreover be liable to disturb the instrument accidentally, and the temporary proximity of the hand and face of the observer would certainly be liable to produce thermic errors.—G. C. Hg.

that a certain improvement might be obtained by attaching the mirror to the frame 3 braced against the test-piece, instead of to the movable frame 2, which should carry the spring 8. This would at least reduce those errors of readings produced by the change of length of the axis of mirror as related to that of the line of sight. In such arrangement the spring 8 should of course be hinged on 2, and pressed against the roller by means of a spring fixed to the same; the spreader 5 must then be connected to frames 2 and 3 in such manner as to avoid constraint.

The errors of reading on a flat scale exist of course in the Unwin instrument, as stated in (*86* and *95*). It will appear that the Unwin instrument requires careful examination of its theory and sources of errors. For regular motions it will be necessary to construct corrective tables, arranged according to magnitude of readings, especially when frame 3 is provided with a level. I could of course merely discuss those points which study would develop, and must refrain from expressing an opinion, because I have not used the apparatus.

705. Although I am not a friend of single-mirror instruments, as previously stated, I shall describe one shown in Fig. 596, designed by myself, because in it the attempt was made to design it in such manner that no constraint is produced by the individual details, and because I intend to use it, in a manner to be described later on (*716*), for photographic records of mirror-motions up to the yield-point, by use of a concave mirror.

To the test-piece are clamped frames 2 and 3 by means of pointed screws 4 and 8 attached at the gauge-marks of length l_t, the lower of which pivots freely about the screw-points, the upper being steadied in its position without constraint by the forked spring 19. The slot in 19 fits the neck of the screw 4 with very slight play. The two rods 11 stand on the screws 9 of the lower frame; the points of 4, 8, and 9 lie in one plane, very nearly. The upper pointed ends of 11 support

the bridge 12, which carries the mirror 16, constructed as previously described. The bridge 12 is supported freely between points 10 and those of 11, points 10, 4, and 8 of upper frame lying in one plane. To avoid all constraint in 12, the points 10 bear in one case in a punch-mark, but in the other in a V-shaped groove. In this instrument there is some difficulty in determining the distance between the bearing-points of 10 and 11 on upper and lower surfaces of 12; this distance is the short lever-arm (corresponding to diameter of fulcrum in my other mirror apparatus), and must be measured with the accuracy previously stated. Special measuring-apparatus will have to be procured for this purpose. The bridge 12 may be easily adjusted to the same initial position by one of the screws 9, as the lower frame pivots. This may be determined by noting parallelism between 12 and 2, or by a special pointer provided for the purpose. The gauge-length l_g may be determined accurately by providing screws 9 with divisions and a pointer, which is, however, hardly necessary, as the errors in l_g will be unimportant compared with those of the actual mirror apparatus. I hope that the apparatus will work well and reliably, and intend to use it simultaneously with a mirror fixed to the test-bar. Both mirrors to be used for photographic records will be concave, projecting a fixed ray as a point onto the sensitive plate.

d. Microscope-reading.

706. The use of microscope and telescope cathetometers for length measurements has been almost abandoned in testing materials because of the inconvenience and really limited efficiency of these instruments. There are probably few laboratories possessing them at present, and still fewer using them regularly.

It is, however, a different matter to use the microscope for determining the relative displacement of gauge-marks. These devices are in this case nothing but reading-microscopes, as

customarily arranged for micrometric apparatus. Hence I merely refer to Bauschinger's device for thrust-tests as presented in (*196*) and Fig. 139, limiting myself to a description of the following apparatus.

707. Unwin constructed the instrument (*L 240*, p. 226) shown diagrammatically in Fig. 497, for observation of shortening in crushing-tests. The lever 1, forked at one end, surrounds the test-piece in such manner that one branch is provided with two pointed clamping-screws, while the opposite one has but a single screw, all applied in the plane of the lower gauge-marks. It is also provided with an adjusting-screw 3, and supports a silvered plate having a fine line at the extreme end, opposite to a micrometer-microscope, 4. A similar mark is made on the long end of lever 2, which rotates about a point supported by screw 3, and is forked at its short end, each branch having a clamping-screw attached to the specimen at the upper gauge-marks. Screw 3 serves to adjust the relative position of the two marks before test. The distance between the two lines is measured by the micrometer 4. Lever 2 multiplies 2.5 times; it is used for measurements of $\frac{1}{20000}$ and $\frac{1}{50000}$ in. (= 0.000125 and 0.00002 cm). The readings give the crushing of the material free from the effect of parts of the machine.

A few more instruments shall be described, which, although externally similar to the above, are quite different in principle.

Olsen builds an apparatus for crushing and transverse tests, shown in Fig. 498. The base 1 supports a parallel motion, forming the short arm of lever 2, and the scale; an adjusting-screw is provided at 3.

Another instrument made by Olsen is shown in Fig. 499. It is supported in two points on a rigid part of the machine-frame, and bears on the lower pressure-platen by two contact-arms immediately beside the test-piece. These two arms are connected by a cross-bolt in such manner that they may be made to bear with equal pressure. The two upper contact-

arms of identical construction bear against the upper pressure-platen. They are supported by a lever the fulcrum of which may be raised and lowered by means of a micrometer, until the screw at the other end makes contact and closes an electric circuit. A second micrometer-screw geared to the first transmits identical motion to the contact-point and the fulcrum. The travel of screw is read on a divided head and a scale, and indicates $\frac{1}{1000}$ in. Great reliability cannot be expected, as it is very difficult to obtain identical screws, because of the transmission of motion by gearing, and because of awkward design of support of the lever on the micrometer-spindles.

708. Prof. J. A. Ewing, Cambridge, England, designed a reading-microscope shown in Figs. 500 and 501 and diagrammatically in Fig. 502. The two frames 2 and 3 are clamped to the gauge-marks at distance l_g by means of two pairs of pointed screws; both can rotate freely about these points. The cross-head 4 is supported on pivots in 3 (which lie in the plane of the clamping-screws), and is rigidly connected by two rods with 5, which carries the micrometer 6, having a spherical end resting in a conical hole in 2. The reading-microscope 8 is suspended by bars 7, hinged at their upper end to 4. 9, Fig. 500, is a screw used for adjustment of the microscope to the glass scale mounted on 2 and illumined by a prism behind it. The microscope and unilateral cross-heads 4 and 5 are counterbalanced on the pivots 12 by the weights 10 and 12 in such a manner that the unbalanced weight of frame 2 causes unconstrained contact between the spherical end of micrometer and the conical hole in 2. 9, 10 and 11, Fig. 501, is an adjusting-device which serves to place frames 2 and 3 into their correct initial position during attachment.

When the test-piece is elongated an amount equal to λ, Fig. 503, the end of micrometer will describe a circle, having the upper clamping-screws as a centre, swinging through the angle

β. The microscope must also describe the angle β about the upper clamping-screws. The lower cross-head will then describe the angle α depending upon angle β. The value of these two angles depends upon the dimensions of the test-piece and the extension λ of the bar.

The micrometer-screw 6 is used principally for adjusting the scale to 0; it is not necessary to change it during the test, as the dimensions have been so chosen that the scale does not move beyond the field of view of the microscope.

It will be readily seen that the theory of the instrument is complicated, and that the angular motion of microscope-support and of movable cross-head must become sources of error, because the sharpness of adjustment varies. The practical value of the errors indicated cannot be decided without careful calculation and practical calibration of the instrument. The author states that readings with his instrument may be estimated to $\frac{1}{50000}$ in. ($=0.000508$ mm) (*L* Proc. Royal Soc., Vol. 58).

C. Autographic Recorders for Stress-strain Diagrams.

709. I have previously described a great number of autographic recorders, because the devices are often more or less inseparable details of the machines. Therefore a repetition must be avoided, and I shall confine myself to a reference to the apparatus previously described, while amplifying the omissions, and presenting the fundamental principles of construction of recorders. It is not possible to discuss all of the known apparatus tried for the purpose or intended therefor, because their number is exceedingly great.

A systematic classification of automatic recorders, in accordance with definite principles, is indeed very difficult, and as it cannot be complete, I shall not attempt it. To

illustrate the multiplicity of types, I will state that there are such as draw lines and others which write figures. In testing materials the former are the rule. Among diagramming, machines there are those which draw continuous lines (the usual type) and others interrupted lines (Unwin, Rudeloff and others). They record either on plane or on cylindrical surfaces; in some a long strip of paper travels through them (Martens oil-tester). The record is made on paper, smoked glass, or on sensitive plates, etc.; it is made in ink (color) or pencil on ordinary paper, or by metal points on prepared (indicator) paper. The kind of pen is manifold. Records are made on a diminutive [Martens 1000-kg machine (*546*)], medium [Henning (*725*)], or largely magnified scale [Unwin (*728*), Gray (*723*)]. In one case large record of loads is emphasized; again, deformations are greatly magnified. One is satisfied to record deformations beyond the elastic period on a moderate scale, another requires his apparatus to record deformations within the yield-point very greatly magnified [Olsen, Kennedy, Unwin, Gray and others], a third changes the scale of record during the test automatically (Henning). One records diagrams of L and e load and deformation, another desires that stress S and unit elongation e, be indicated [Martens (*716*)]. It may also be arranged to record variations of loads between limits (Martens oil-tester). The method of operating recording detail, of load-indication by the machine, and many other conditions, are controlling in the design of the apparatus.

710. Classification of recorders in distinct groups according to the foregoing is difficult. The simplest method would be based on whether the record is complete or only a partial one recording up to the yield-point. Herein it is necessary to note whether the record produced by the apparatus is merely relative, or illustrative of the properties of the materials tested, or whether the diagram furnishes an accurate record of results of tests, whether they can be determined therefrom by meas-

urement. In the first case the usual observations must be made, additional to the record, and the latter can only be used as a check on the test. In the second case the observations are merely a verification of the record. [The views on this subject held at the Charlottenburg Testing Laboratory have been developed in (*534*)].

In apparatus of the latter type it should be strictly required that the effect of the existing sources of error be absolutely limited to the unavoidable limit, and that the ultimate effect of all sources of error, arising from the entire apparatus, be smaller than the limits of error arising in careful measurement of the diagrams produced. If the instruments do not fulfil these requirements their records cannot, contrary to the views of the designers, be considered as anything more than illustrations, which, however, have valid reasons for existence and may be of great utility.

It might really be considered hardly necessary to discuss these self-evident matters at such great length. But careful study of previous chapters will have carried conviction of the fact that designers of testing-machines and measuring-apparatus have not always completed their designs to the last detail. He who will take the trouble to look over the literature of the subject will note with astonishment how even noteworthy investigators have neglected the considerations here discussed. I emphasize this point particularly because I thereby hope to encourage thoroughness and constant self-control.

I shall take up the discussion of recorders in the order in which they are presented on the plates at the end of the work, inserting others not illustrated in their proper place.

711. No recorder is in use on the Werder machine to my knowledge. Years ago I tried to adapt the idea applied to the 1000-kg machine (*546*), and to utilize the extension of the tension-rods as a measure of force. But the device would have been too complicated, and I therefore dropped it. In my opinion it will be most suitable to use independent disconnected apparatus in connection with the Werder machine.

712. The recorder for my 50-ton machine (Pl. 5, Fig. 3) has been described in (*563*), where the development of a series of designs is given. I merely wish to repeat that exceedingly sensitive electrical apparatus may be developed, which are at the same time, however, mostly very difficult to operate, and to show that experience always leads back to simplicity. How the same end may be reached by hydraulic means is shown by the example given in the description of my 5000-kg machine (*499*).

713. The limits reached by the use of complicated apparatus is illustrated by the Fairbanks & Co. so-called diagramming apparatus (A. V. Abbott, designer), which I have described in (*L 113*).

[This apparatus was so extraordinarily complicated and contained such impossible detail, as strings twenty (20) feet long, etc., that it was quite useless and always out of order; it has disappeared totally.—G. C. Hg.]

714. In the Mohr & Federhaff recorder, Pl. 6, Fig. 1, and Pl. 7, Figs. 1, 3 and 4, the drum is revolved by the relative motion of the holders, recorded as extension, while the poise-travel is recorded on a reduced scale. The extension of gauge-length of test-piece proper is therefore not recorded.

715. The Grafenstaden autographic recorder, Pl. 8, Figs. 3, 10, 29 and 30, records by revolving the paper drum by poise-travel, while the motion of the driving-spindle which operates the pencil is recorded as extension. In this case the record of extension is still more affected by action of machine-detail than in the previous case.

716. The autographic recorder designed by me for the Pohlmeyer machine, Pl. 9, Figs. 19–27, has already been described in (*534*). I now desire to discuss an idea, new as far as my knowledge goes.

I have previously (*532*) called attention to the fact that the Pohlmeyer machine may be easily arranged so as to make the pedestal 23 adjustable on a scale divided according to

cross-sectional areas a of test-piece, thus reading stress S on the load-indicator directly. If then extension be also recorded on a scale proportionate to e_1, the advantages of record of S and e_1 previously described in (*40*) will be secured.

If elastic deformations are to be recorded with the same accuracy obtainable by mirror apparatus, this may be done by photographic means as shown in my concave-mirror apparatus described in (*705*). It is only necessary to move the sensitive plate vertically to the plane of the ray of light reflected from a projector, and to make this motion dependent upon the indicator 40, Fig. 19, Pl. 9; this can be readily done in several ways.

The photographic plate, even at the present day, may be used for very delicate measurements, so that it is hardly necessary to make the angular motion of mirror very great; i.e., scale of extension e_1. But even this would not be objectionable in connection with the Pohlmeyer machine, if the photographic apparatus be so arranged that the camera be carried by the rod 40. Its rise relatively to a fixed luminous point would then give the measure of stress S (or load L). If now the reflected ray for recording e_1 also move in a vertical direction similar to that of the camera, only the difference between the two motions will be recorded. If, however, the plate or camera be moved horizontally and normally to the ray of light, which can be easily done, either proportional to stress increments (load) or proportional to time, the record will be a straight line for materials having constant e_f up to the proportional limit, at an angle of e_1/S with the horizontal, becoming a horizontal in the special case when values of e_1 and S become equal in the diagram.

For scientific investigations, especially of the behavior of iron (steel) at the yield-point, this idea may be of some importance, because great accuracy of record may be obtained in addition to sensitiveness. I believe that the study of the behavior of metals having variable e_f and subject to important residuary phenomena, such as concrete, leather, magnesium, etc., will

thereby be greatly facilitated. (The future will probably demonstrate that materials having such properties are the rule, and that those having unchangeable e_f are, to a certain extent, exceptions.)

717. I have made use of the principle of differential record in several recorders designed by me for the Charlottenburg Testing Laboratory, as in several forms of lubricant-testers.

In the type shown in Fig. 506 (*L 230*) the slide 4, moving on rollers 5, is actuated by a roller on the pendulum 2 moved by the journal 1 under test. The swing of the pendulum may be directly read on a scale on the slide, graduated according to the constants of the machine, so that its readings multiplied by the length of pendulum give the factor of friction directly. As a rule this number varies but little during the test of any lubricant, and therefore a relatively narrow strip of paper suffices for the record. To produce the latter, the pencil 6 is adjustably connected to 4. The drum 7 is operated from 1 by means of worm-gearing 8, 9 and 10.

The second oil-tester shown diagrammatically by Fig. 507 has the object of determining the durability of a definite quantity of lubricant placed between the conical friction-surfaces 3 and 4 under different pressures, as well as the character of the derivative materials, which are evidently produced from the oil, subject to work. The cone 3 is driven by the belt 16. Lubrication is made intermittent, or continuous by means of pipes, issuing in the space at upper end of the funnel 4, used for exhausting the gaseous products. The funnel 4 is forced down by a Napoli pressure-gauge, described in (*556*), and the friction produced is measured by the scale 9 attached to lever 8, which is attached in a horizontal plane to 4. The frictional resistance is mainly counterbalanced by the weight P, and its variations by the variations of stress in spring 11. The scale-beam 9 vibrates between stops 10, thereby limiting the motion of the pencil to a narrow strip of paper.

718. The Hartig-Reusch (*542*) and Leuner (*544, 545, 548, 549*) autographic recorders have been previously described and shown in Pl. 11. The Kennedy (*547*) and Martens (*546*) recorders using standard bars may be grouped with the Leuner devices.

719. The Amsler-Laffon autographic recorder is shown on Pl. 14, Fig. 8, and schematically by Fig. 508. It is very complicated in design, but by use of the scheme the illustration on Pl. 14 will probably be understood. Loads are recorded by a float on the mercury-column of the gauge (*561*), a string, 19, from which is wrapped around 18, thus moving the pencil-carrier 17, mounted on rollers, across the drum 15, revolved in proportion to deformations. The transmission of deformation is peculiar.

Two contact-points are attached to the test-piece at the gauge-length, against the inner surfaces of which two feelers, 3 and 4, bear. The feeler 4 is lightly pressed against the contact-piece by the counterpoise on the lever 5, while the other feeler is kept in contact by an automatic adjusting-device. The latter may be very variedly designed, as I showed in my report (*L 1*, 1884, p. 102). Amsler-Laffon employs a micrometer-screw 6 in the frame 4, which is operated by the weight 13 and the gearing 12, 11, 10, which at the same time revolves the drum 15 by means of gearing 14. These motions are, however, controlled by the lever 3. This is done by lowering the frame 7 and nut 7 by means of screw 6, until the lever 3 forces pin 9 upwardly until it engages a tooth on the crown wheel 8 supported by frame 7; this arrests the crown wheel and the apparatus, until further extension releases the crown wheel. The apparatus must therefore accurately follow the deformations recorded on the paper on a tenfold scale.

The recorder rests on a bracket clamped to one of the columns of the machine, and may therefore be adjusted to the position of the test-piece by swinging the bracket into proper position. I can say nothing about the capabilities of the ap-

paratus, as I have not used it. Whether a tenfold magnification of deformation is always convenient is no doubt questionable. It is certainly not sufficient for determining the *P*-limit, although it may become very useful for observing phenomena of flow. The mechanism 20 and 21 served for readjustment and reversing the screw 6 after test.

720. Olsen solved the problem of mechanical readjustment of his recorder as shown schematically by Fig. 509. The fundamental principle in this is again to revolve the drum 12 by the extension of the test-piece, and to move the pencil 13 across it by means of the travel of poise 10 on the beam 9. Two frames, 2, are clamped to the gauge-marks l_1 by means of spring-cushioned screws and a specially complicated device, designed with a great display of ingenuity. I pass over the description of this device, shown on Pl. 20, Fig. 13, because a small error of adjustment to length is unimportant as compared with those of the apparatus.

The two forked contact-levers with revolving ends, 3 and 4 [not shown in Fig. 509, but on Pl. 20, Fig. 12, and especially by Fig. 499 (707)], bear against the frames 2. The lever 4 transmits all motion of the upper frame, 2, by means of the metal band 16 to the lever 5, and its roller, 6, which latter transmits it by means of the band 8 attached to the end of 7, acting in the vertical plane of the main knife-edge of lever 9, on the roller 11 of the drum 12, without exerting a moment of force on the scale-beam 9. The lower contact-lever 3 transmits the motion of the lower ring 2 to the lever 7 by means of a band, 14, tensioned by a counterpoise on lever 15. As all levers have such ratios that the motion of lever 7 is equalized by the motion of the complete mechanism, the relative motion of frames 2, the extension of test-piece, is alone recorded. The apparatus is undoubtedly ingeniously constructed, but the previously stated considerations relating to sources of errors of recorders must be borne in mind if they are to be used for anything more than the simple recording of diagrams.

The apparatus is shown as applied to several machines on Pl. 20.

721. Olsen exhibited a different apparatus at the Chicago World's Fair, 1893. In order to record the extension of l_r during the elastic period, he used a micrometer in a peculiar manner (*687*), as shown schematically in Fig. 510. The micrometer-screw 6 controls, by electric contact of 6 and 7, an electric brake on a belt operating the screw 2. The spindle of screw 2 is provided with a gear, which drives the wheel 5 carried by the micrometer 6 until contact is made by the latter. Hence screw 2 must follow the extension of the bar, and its elevation will then act on the contact-lever of the autographic recorder described in (*720*). If the errors of the micrometer apparatus mentioned in (*687*) be reduced, and the double task of spindle 2 be avoided by separating its two functions of driving and its use as a screw, it would be possible to obtain very good diagrams.

722. If the suggestion made by me (*719*; *L 1*, 1884, p. 102) in regard to a micrometer apparatus, perhaps as described in (*688*), Fig. 470, be adopted, very perfect diagrams might be obtained, provided the micrometers were driven by two electrically controlled operating mechanisms, with, say, single or multiple reduction by worm-gearing in such manner that it tends to produce contact and brakes the mechanism at the instant of contact. Both mechanisms should be coupled together, perhaps, by planet-wheels, so that the pencil or the paper moves proportionately to the sum of their revolutions. By this arrangement any desired magnification of record may be obtained, although only with the addition of all errors of screws and the parts of the apparatus. It is of course necessary to reduce the motion required for making and breaking contacts to a very small amount, so that not more than 0.00004 in. (0.001 mm) play is requisite. Hence the applicability of very weak currents, with relays and microphone contacts, etc., should be examined. Whether the examination

will be profitable is certainly doubtful; I think that the photographic method is more promising (*705, 716*).

723. Riehlé Bros. also construct an autographic recorder for records of elastic extensions. This Gray recorder, Pl. 19, Fig. 18, is shown schematically in Fig. 511. The operation of the drum by means of string and roller and the poise-travel is limited; all other motions are transmitted by levers, fulcra and rods. Extension is transmitted to the pencils by means of levers in the following manner: The contact-levers 3 and 4 bear against the rollers 2, and are connected by a rod, 5. The lower lever, 3, is supported by screw 6 attached to the machine-frame; the upper, 4, rests on the upper ring, 2, supported by the rod 7. This causes 3 to bear against the lower frame 2, because the lever system is slightly overbalanced in that direction. Hence like motions of both frames in the direction of axis of test-piece are not recorded; only relative motion between the frames 2 is recorded.

Elastic extensions are transmitted to the pencil 12 by levers 8–11 on a scale of 100/1 to 500/1, accordingly as the rod 9 is connected at the different points *a–e*. The recording paper may thus be efficiently utilized, because the pencil may be adjusted to the zero-line for any load by adjustment by means of screw 6, and then recording the further progress of the diagram.

The other pencil, 14, serves to record the diagram for the whole test on a smaller scale by means of the lever 13, the ratio of which may be altered by shifting its fulcrum from *a* to *c* as desired. The motion of the drum 15 is changeable by means of a stepped pulley having 5 grooves. It must be said that the construction is clear and complete; and although I had no opportunity of using it, it seems clear to me from my previous experience that it might work satisfactorily. The parts are simple, and good workmanship should be readily attainable. The support is rigid, and will hardly lead to errors caused by the deformation of supporting parts, espe-

cially as adjusting-screw 6 might be readily connected to the base-plate of the apparatus, and thereby be disconnected from the testing-machine itself, without decreasing the accuracy of transmission.

The magnification of 1 : 500, however, probably exceeds the limit allowable in a mechanical recorder. The friction of the pencil on the paper is increased in the same ratio, and hence friction of 0.00022 lbs. (= 0.1 g) will produce a difference of pressure at the ends of contact-levers by loading and unloading of 0.22 lbs. (= 100 g). All deformations of levers change accordingly, and the magnitude of the errors thereby produced is questionable. That the constructor recognized this fact is clearly shown by Fig. 18, Pl. 19. The friction may of course be determined by adjustment during absolute rest, first from below and then from above, by the difference between the positions of the pencil; or it may be eliminated by constant, perhaps electric, vibrations of the drum, but the effect of the inert masses will remain.

724. In view of the fact that it has been frequently attempted, especially in the United States and Great Britain, and it is still attempted, to record elastic extensions during tension-tests on a *very largely magnified scale* by means of autographic recorders, thereby to determine the limits of perfect elasticity, I desire to again state that, in my opinion, *this problem is very difficult to solve satisfactorily by mechanical means, and is practically unnecessary.*

The only point within the elastic limit determinable by autographic recording is the proportional (P-) limit. This is, however, very difficult if it is to be done accurately, and is only possible with instruments as delicate as our mirror-apparatus. With these, readings of 0.0000013 in. (= $\frac{1}{30000}$ mm), and less, are easily obtainable, and it will then be still found that the elastic material shows a gradual merging of the straight into a curved line. At present there is no practical value in enter-

ing this field; to record such dimensions by mechanical means is practically unattainable; it would be better to resort to optical means, if it becomes necessary, to cause the machine to record them. What should be attempted is to adapt the mechanical autographic recorder to practical work. And what is of practical value is that part of the curve near the yield- (*Y*-) point, and beyond it to the instant of rupture. The transition from the P-limit to the curved part of the line will probably be recorded always with great uncertainty (even with optical means), and in my opinion low ratios of multiplication should suffice for mechanical records, which give the conditions at the yield-point most clearly. It is profitable to use a very delicate instrument for this point only when a machine sufficiently reliable for such tests is available, and which does not obscure the results of load-indication by inertia of the masses. Great magnification of record of this part of the curve is valuable only in case where it is desired to make scientific investigations with greatest accuracy. Where the diagram is to serve purposes of instruction alone, or, indeed, practical purposes, the attempt should always be made **to produce it with the very simplest means applicable,** and in case of need one should be content to obtain it merely as an illustration.

725. That which is practically sufficient seems to me to be embodied in the fundamental principles of the Henning (New York) Pocket Recorder. The apparatus has the great advantage that it may be carried about like a steam-engine indicator, and used in connection with all machines having a motion of any part proportional to the stress transmitted by the test-piece. The drum is revolved by a string connected to such moving part (poise-weight, pendulum, frame of punch or shears, etc.), while deformations of test-piece are transmitted to the pen by the apparatus attached directly to the test-piece, first with a tenfold magnification; after passing the yield-point, and at any desired instant thereafter, the ap-

paratus automatically ceases to multiply deformations, and then records them on natural scale. The apparatus can be very readily attached to any test-piece, and remains thereon until after rupture. Its construction is shown in Fig. 512.

Two openable hinged frames, 2 and 3, are attached to the test-piece 1 at the gauge-length by adjustable spring-cushioned knife-edges, and connected by rods 4. These rods 4 attached to frame 3 are of such length that when inserted in tubes 4 attached to the frame 2 and made to abut, the distance between knife-edges will be precisely $= l_r$, and hence the gauge-marks need not be made on the test-piece. The lower frame, 2, also has two rods 5, which serve as guides, for the actual recording mechanism 6–8. This is mounted on the frame 6, which slides on the rods in elastic sleeves in such manner that their friction will cause 6 to stand in any desired position. On the frame 6 a lever system, such as is commonly used in indicators, and parallel motion of levers 7 and pen 8, is mounted. The lever 7 is connected to the frame 3 by a rod 9. The relative displacements of frame 2 and 3, i.e., the extension of gauge-length of test-piece, are transmitted to the lever 7, as the frame 6 retains its position relatively to 2 because of greater friction on 5. Extensions of the test-piece are therefore recorded on drum 10 on a multiplication of that of the levers. That the ratio must vary with the angularity of the lever is self-evident from the theory underlying the parallel motion; the error may, however, be practically neglected, unless extravagant demands be made of the apparatus. The drum 10 is revolved by friction of a stepped sheave on its edge. This sheave may be adjusted to any desired position by the arm 12, so that the tension of string 13 causes the sheave 11 to bear against the rim of the drum in every position. The adjustable hook 14 is used for the purpose of arresting the lever 7 in any desired position. It is adjusted to such a position that the pen records the magnified deformation a little beyond the yield-point. As soon as this point has been passed the motion of

lever 7 will be arrested, and thereafter extension will be recorded on a scale of 1/1, because the stress in rod 9 will overcome the friction of sleeves 5, and moves the entire recording mechanism as a unit. This idea is very ingenious.

The very light parts do not suffer injury at instant of rupture; at most there is slight slipping of the knife-edges on the test-piece, thus producing distinct marks on it, which facilitates checking records of deformation materially. If the testing-machine permits great separation of the two ends of the broken test-piece, no harm comes to the apparatus, as it will simply separate into two parts, the rods 4 and 5 sliding in and drawing out of their respective tubes.

The delicate apparatus can be conveniently carried about in a small box, and can be readily attached, as it is merely necessary to open the frames and clamp them around the test-piece. The pen may be adjusted to 0, if necessary, by moving the bridge 6 on the rods 5. The apparatus can be used for tension, crushing, and alternate tension-crushing, as well as for punching, shearing, and other tests. How it behaves in practical work I cannot state from personal experience; I believe, however, that it will be efficient.

726. Of the English apparatus I name the autographic recorders of Unwin (*L 240*, p. 236) and of Kennedy (*547*). An apparatus for the Wicksteed machine is shown on Pl. 16, Figs. 3, 5, 8 and 10. In it the drum 36, Fig. 10, is revolved by the test-piece 40 by means of a string, proportionately to extensions, while the motion of the pencil is operated by the driving mechanism of the poise-weight. The string in passing from the test-piece to the drum is guarded by roller-links 37, as described in (*534*), but the hinges of the links do not lie in the circumferences of the rollers.

727. Wicksteed designed another recorder for his machines (*L 240*, p. 134; *236*, p. 27). Its principles are shown by Fig. 513. The string 3 transmits the extension of test-piece 1 to the drum 5. Stress is recorded in a circuitous

manner, strange to say, although the motion of the poise-weight might have been readily used therefor without difficulty. Wicksteed, instead, used the pressure in the hydraulic cylinder in an auxiliary cylinder 7, the plunger of which compresses a spring 6, the deformation of which, as a measure of force, is transmitted to the pencil. In order to eliminate the friction in cylinder 7, its plunger is revolved by the mechanism 8.

728. Unwin constructed another recorder, which is, however, not autographic. In it the drum is revolved proportionately to the motion of the poise-weight. The pencil is moved by an electric contact device in the hand of the operator, so that the latter can cause it to advance or recede by a definite small amount at any instant.

The observer stands at the extensometer, say a mirror apparatus, and signals as soon as the cross-hairs coincide with any even reading, say $\frac{1}{10000}$ to $\frac{1}{10000}$ cm. Hence it is to a certain extent a record of readings. In this method the errors of intermediate apparatus are eliminated. Fig. 514 is an illustration of such a record (*L 240*, p. 239).

INDEX.

A

B

I

J

K

U

V

W

Y

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